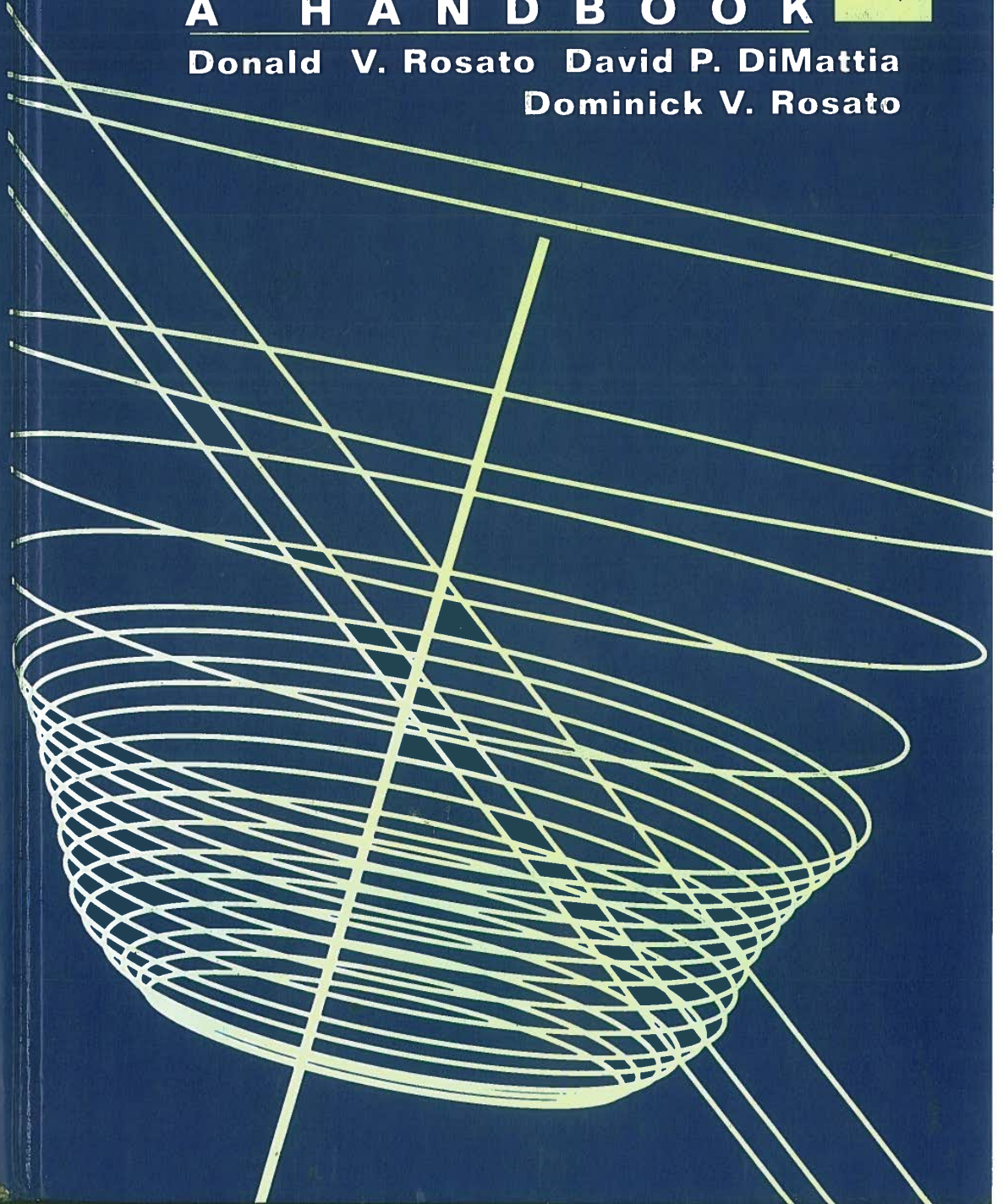


DESIGNING^{with} PLASTICS^{and} COMPOSITES

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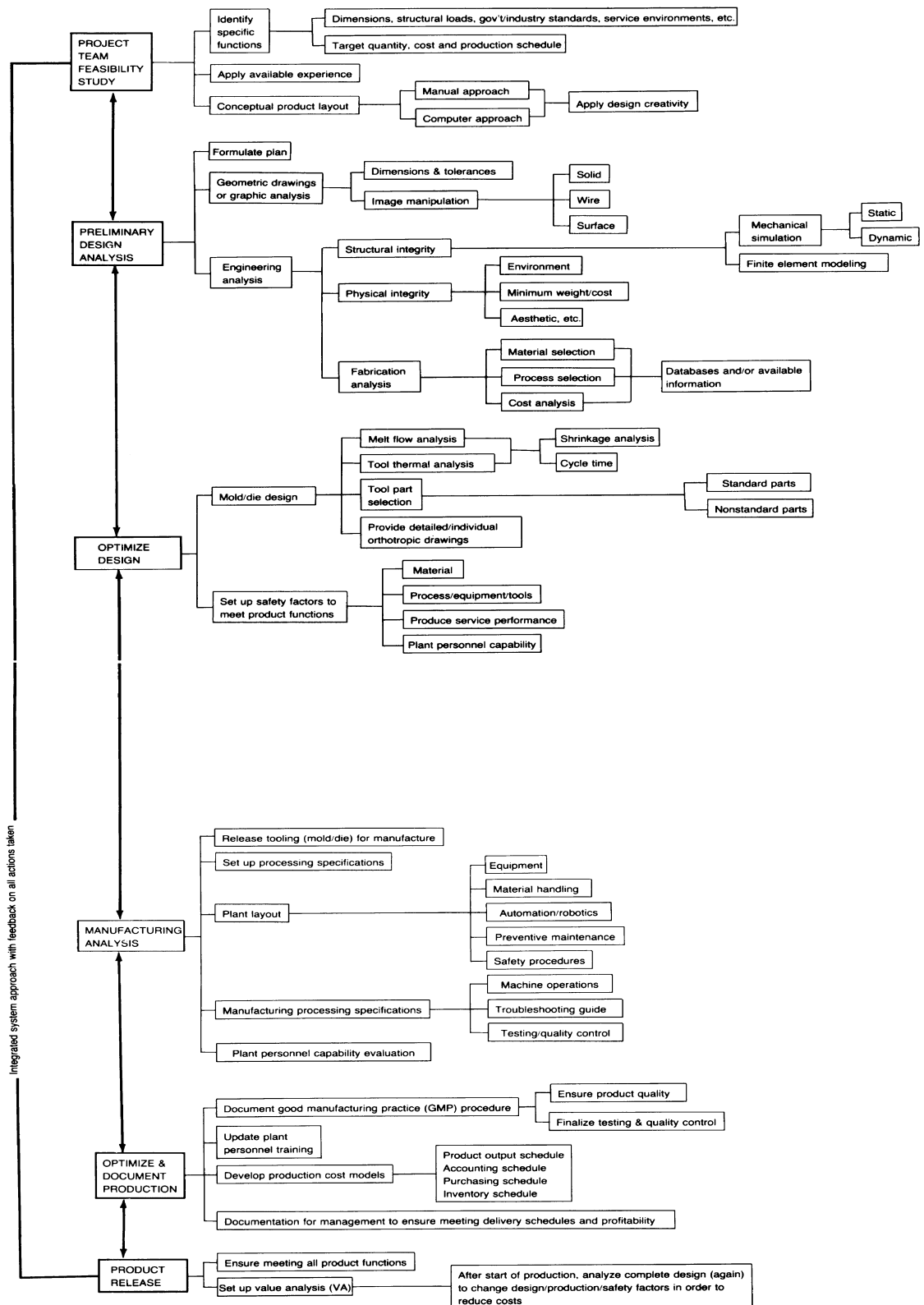


Donald V. Rosato David P. DiMattia
Dominick V. Rosato



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abello@ssjr.com

DESIGNING WITH PLASTICS AND COMPOSITES: A HANDBOOK

Donald V. Rosato, Ph.D.

David P. Di Mattia

Industrial and Graphic Designer

Dominick V. Rosato

P.E. Rhode Island School of Design



SPRINGER SCIENCE+BUSINESS MEDIA, LLC

Copyright © 1991 by Springer Science+Business Media New York
Originally published by Van Nostrand Reinhold in 1991
Softcover reprint of the hardcover 1st edition 1991

Library of Congress Catalog Number 90-46378

ISBN 978-1-4615-9725-4 ISBN 978-1-4615-9723-0 (eBook)
DOI 10.1007/978-1-4615-9723-0

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16 15 14 13 12 11 10 9 8 7 6 5 4 3 2

Library of Congress Cataloging-in-Publication Data

Rosato, Donald V.
Designing with plastics and composites: a handbook
by Donald V. Rosato, David P. Di Mattia, and Dominick V. Rosato.
p. cm.
Includes bibliographical references and index.

1. Plastics. 2. Engineering design. I. Di Mattia, David P.
II. Rosato, Dominick V. III. Title.
TP1122.R67 1991
668.4'9--dc20 90-46378
CIP

Contents

Preface / ix

1. FUNDAMENTALS OF DESIGNING WITH PLASTICS AND COMPOSITES / 1

Design Shape / 49
Success by Design / 51
Computers in Design / 52
Design Procedure / 54
Interrelating Product-Resin-Process Performances / 55

2. THE STRUCTURE AND BASIC PROPERTIES OF PLASTICS / 61

Plastic Structures and Morphology / 66
Thermal Properties of Plastics / 83
Thermal Conductivity and Thermal Insulation / 87
Heat Capacity / 88
Thermal Diffusivity / 88
The Coefficient of Linear Thermal Expansion / 89
Deflection Temperature Under Load / 94
Decomposition Temperature / 95
Mechanical Properties / 96
Physical Properties / 98
Rheology and Deformation / 107
Interrelating Properties, Plastics, and Processing / 116
Orientation / 118
Shrinkage / 123

3. PLASTICS: DESIGN CRITERIA / 125

Mechanical Properties / 133
Short-Term Behavior / 135
Long-Term Behavior / 153
Short-Duration Rapid and Impact Loads / 201
Electrical Properties / 223
Friction, Wear, and Hardness Properties / 239

iv CONTENTS

4. ENVIRONMENTAL CONDITIONS AFFECTING PLASTICS / 253

Temperature Introduction /	253
Chemical Resistance /	264
Weather Resistance /	272
Sterilization-Irradiation /	274
Permeability and Barrier Resistance /	276
Biological and Microbial Degradation /	281
Flammability /	282
The Ocean Environment /	288
The Space Environment /	297

5. STRUCTURAL DESIGN ANALYSIS / 303

Load-Bearing Products /	303
Loads /	305
Support Conditions /	305
Simplifications and Assumptions /	308
Multiaxial Stresses and Mohr's Circle /	308
Safety Factors /	309
Beam Bending Stresses /	312
Beam Bending and Spring Stresses /	321
Shear Stress and Torsion /	323
Shear Stress and Direct Shear /	325
Pressure Vessels /	325
Externally Loaded RP Pipe /	326
Molded-In Inserts /	340
Press Fits /	342
Snap Fits /	345
Hinges /	349
Thread Strength /	355
Pipe Threads /	358
Gears /	359
Gaskets and Seals /	360
Grommets and Noise /	360
Impact Loads /	361
Thermal Stresses /	362
Structural Foams /	365
Structural Sandwiches /	368
Energy and Motion Control /	371
Failure Analysis /	387
Dimensional Tolerances /	387
Plastics /	388
Processing and Tolerances /	391
Product Specification /	398
Combining Variables /	399
Finite Element Analysis /	399
Cantilevered Snap Fits /	402
Laws and Regulations /	402

6. THE PROPERTIES OF PLASTICS / 405

Trade Names /	405
Acrylonitrile-Butadiene-Styrene (ABS) /	406
Acetal /	414
Acrylics /	415
Alkyds /	416
Aminos /	416
Cellulosics /	417
Chlorinated Polyethers /	417
Chlorinated Polyethylene /	418
Cross-Linked Polyethylene (XLPE) /	418
Diallyl Phthalate /	418
Epoxies /	419
Ethylene-Vinyl Acetates /	419
Fluoroplastics /	420
Furan /	421
Ionomers /	421
Ketones /	422
Liquid Crystal Polymers /	422
Melamines /	423
Nylons (Polyamides) /	423
Parylenes /	425
Phenolics /	426
Phenoxy Resins /	427
Polyallomers /	428
Polyamides /	428
Polyamide-imide /	428
Polyarylates /	430
Polyarylethers /	430
Polyaryletherketone /	430
Polyarylsulfone /	431
Polybenzimidazole /	431
Polybutylenes /	432
Polybutylene Terephthalate /	432
Polycarbonates /	432
Polyesters /	433
Polyetherketone /	436
Polyetheretherketone /	438
Polyetherimide /	439
Polyethersulfone /	440
Polyethylene /	440
Polyethylene Terephthalate /	445
Polyimides /	445
Polymethyl Methacrylate /	445
Polymethylpentene /	446
Polyolefins /	446
Polyphenylene Ether /	446
Polyphenylene Sulfide /	447

vi CONTENTS

Polypropylene /	447
Polystyrene /	449
Polysulfones /	449
Polyurethane /	452
Polyvinyl Chloride /	452
Polyvinylidene Fluoride /	455
Silicones /	455
Urea Formaldehydes /	456
Elastomers /	458
Thermoset Elastomers /	467
Thermoplastic Elastomers /	472
Film and Sheeting /	473
Foams /	475
Transparent and Optical Plastics /	491
Reinforced Plastics and Composites /	493
Regrind and Recycling /	524
Guide for Plastics Identification /	525
Computerized Databases /	528
Selection Worksheets /	535
Selecting Materials /	535
Selecting Materials under Dynamic Loading /	540

7. THE PROCESSING OF PLASTICS / 589

Tolerances and Shrinkages /	596
Model Building /	596
Molds and Dies /	599
Drying Hygroscopic Plastics /	602
Heat History, Residence Time, and Recycling /	602
Process Control /	603
Troubleshooting /	603
Inspection /	606
Injection Molding /	610
Extrusion /	624
Basics of Flow /	630
In-Line Postforming /	641
Blow Molding /	646
Extrusion Blow Molding /	651
Forming /	665
Reinforced Plastics/Composites /	670
Other Processes /	687
Selecting Processing /	695

8. AUXILIARY EQUIPMENT AND SECONDARY OPERATIONS / 711

Material Handling /	713
Parts Handling /	713
Finishing and Decorating /	714
Joining and Assembling /	714
Machining /	727

9. TESTING AND QUALITY CONTROL / 731

Basics versus Complex Tests / 732
Specifications and Standards / 732
Orientation and Weld Lines / 734
Types of Tests / 735
Thermoanalytical Tests / 735
Nondestructive Testing / 746
Computer Testing / 753
Quality Auditing / 753
Reliability and Quality Control / 754
Failure Analysis / 754
Selecting Tests / 755
Quality and Control / 755

10. COMPUTER-AIDED DESIGN / 757

Mold Design / 758
CAD/CAM Modeling / 763
Additional CAD/CAM Features Used in Plastic Part and Mold Design / 773
Process-Analysis Tools / 777
Design Databases / 782
Computer-Integrated Manufacturing / 785
Myths and Facts / 785
Capability and Training / 786

11. DESIGN FEATURES THAT INFLUENCE PERFORMANCE / 789

Basic Detractors and Constraints / 789
Injection Molding / 796
Extrusion / 844
Blow Molding / 847
Thermoforming / 854
Reinforced Plastics and Composites / 856
Rotational Molding / 865
Assembly Methods / 869
Mechanical Loading / 870

12. CONCLUSIONS / 877

Product Diversification / 879
Materials Diversification / 883
Equipment Improvements / 887
The Solid-Waste Problem and Product-Design Solutions / 889
Technical Cost Modeling / 898
Success by Design / 900
Design Considerations / 900
Challenge Requires Creativity / 914
The Future / 915

viii CONTENTS

Appendix A. General Information Sources	/ 919
Appendix B. Conversions	/ 921
Appendix C. Trade Names	/ 925
Appendix D. Computerized Software and Databases	/ 929
References	/ 937
Index	/ 967

Preface

For some time there has been a strong need in the plastic and related industries for a detailed, practical book on designing with plastics and composites (reinforced plastics). This one-source book meets this criterion by clearly explaining all aspects of designing with plastics, as can be seen from the Table of Contents and Index. It provides information on what is ahead as well as today's technology. It explains how to interrelate the process of meeting design performance requirements with that of selecting the proper plastic and manufacturing process to make a product at the lowest cost. This book has been prepared with an awareness that its usefulness will depend greatly upon its simplicity. The overall guiding premise has therefore been to provide all essential information. Each chapter is organized to best present a methodology for designing with plastics and composites.

This book will prove useful to all types of industrial designers, whether in engineering or involved in products, molds, dies or equipment, and to people in new-product ventures, research and development, marketing, purchasing, and management who are involved with such different products as appliances, the building industry, autos, boats, electronics, furniture, medical, recreation, space vehicles, and others. In this handbook the basic essentials of the properties and processing behaviors of plastics are presented in a single source intended to be one the user will want to keep within easy reach.

Once a product's purpose and service requirements have been established, its successful design and manufacture to meet zero-defects production requires knowledge of 1) the plastic materials from which it is to be made, their nature, and the ways in which processing may affect their properties; 2) the processing methods available for its manufacture; and 3) how to evaluate its properties and apply effective quality control.

This reference handbook has been designed to be useful to those using plastics as well as those still contemplating their use. To this end the presentations are comprehensive yet simplified, so that the specialist in a specific field will obtain useful information. The cross-comparisons and interrelations of design facts and figures are extensive, to ensure ease in understanding the behavior of plastics and composites.

Designing depends on being able to analyze many diverse, already existing products such as those reviewed in this handbook. One important reason for studying these designs is that this shows how many diverse topics cooperate synergistically to enhance designers' skills.

Design is interdisciplinary. It calls for the ability to recognize situations in which certain techniques may be used and to develop problem-solving methods to fit specific design situations. Many different examples of problems are thus presented within this handbook, concerning many products.

x PREFACE

With plastics, to a greater extent than with other materials, the opportunity exists to optimize design by focusing on a material's composition, its structural orientation during processing, and other factors described throughout this handbook. Analyses are made of problems that can occur and how to eliminate them or how to take corrective action. This book is intended to provide practical guidelines to designers using plastics or composites.

Throughout this handbook, examples that relate to basic strengths of materials are given so as to highlight their influence in different designs. The information to the designer includes the behavior of plastics under extreme performance conditions, relates these behaviors to design principles, and provides important information on design parameters as they interrelate with plastic materials, processing characteristics, and the performance of products.

As materials to be fabricated, plastics provide practical, unlimited benefits to the design of products. Unfortunately, as with other materials, such as steel, wood, glass, aluminum, and titanium, no one plastic has all the best traits, so that sometimes selecting a material requires compromising. Successfully applying their advantages and understanding their limitations, as reviewed in this handbook, will allow designers to produce useful, profitable products.

There is a wide variation in the types of properties among the fifteen thousand materials commercially available worldwide that are classified as plastics or composites. In general, however, most plastics can be processed into different shapes and sizes. If so required, they can have intricate shapes held to tight tolerances and be made by processes suitable for either limited or mass production. The costs of plastics range from relatively low to extremely expensive, enough to make a plastic appear to be too costly for a given product. However, studying the processing method could result in meeting low product-cost requirements. This handbook thus provides the designer with useful information on the different processing methods as they relate to meeting design and cost requirements.

Plastics vitally concern almost everyone worldwide. They occupy an important part of the research, development, design, production, sales, and consumer efforts in diverse industries. As reviewed later, for over a century plastics have been used successfully, in such applications as for packaging, housewares, medicine, marine, aerospace, hydro-space, transportation, biological, appliance, building, and recreation. The significant improvements that have been made in plastic materials, processing, and applications thus far will no doubt be overshadowed by future improvements.

Because their broad range of properties makes plastics unique, they are adaptable to different products and markets. With plastics, one can decide on practically any requirement and find for it a processable plastic, whereas other materials have comparatively narrow capabilities. It is nevertheless important to recognize that there are tremendous variations in the properties and performance of plastics. This handbook shows that there is a practical, easy approach to designing with plastics.

One of the major aims of this book is to help develop the designer's ability to analyze problems, a most important skill. Although engineering mechanics is based on only a few basic understandable principles, these principles are needed to provide a means to solve many problems relating to present-day design and analysis. This book emphasizes both understanding and applying these principles, so that the designer will have a firm basis for utilizing the principles.

It is essential to reemphasize the point made in the text that all data presented on plastic properties are to be used only as guides. Obtain the latest, most complete data from material suppliers and data banks from the various sources referenced throughout this handbook.

The information presented herein may be covered by United States or foreign patents. No authorization to utilize these patents is either given or implied; they are discussed as information only. Likewise, the use of general descriptive names, proprietary names, trade names, and commercial designations and the like in no way implies that they may be used freely. They are often legally protected by registered trademarks or some other format even if they are not designated as such in this book. Finally, although the information presented is useful data that can be studied or analyzed that are believed to be true and accurate, neither the authors, contributors, nor publisher can accept any legal responsibility for errors, omissions, or similar factors.

In preparing this handbook extensive use was made of the personal industrial and teaching experiences of the authors, going back to 1939, as well as worldwide information from industry and trade associations on materials, equipment, and the like, published books, articles, reports, conferences, and so on, as is evident in the references given at the end of the book.

In the preparation of this handbook the authors have been assisted and encouraged by many friends and international business associates. Special acknowledgment must be made to the many different authors cited, including many different material suppliers. All have, whether directly or indirectly, contributed to advancing the state of the art in designing with plastics.

Chapter 1

FUNDAMENTALS OF DESIGNING WITH PLASTICS AND COMPOSITES

There is a practical, easy approach to designing with plastics and composites (see Figs. 1-1 to 1-3) that is basically no different than designing with other materials: steel, aluminum, titanium, copper, brass, wood, concrete, and so forth. This book provides useful and necessary information on how to comprehend plastics' and composites' extreme range of properties, structural responses, product-performance characteristics, part shapes, manufacturing processes, and their influence on product performance, the simplifying of designs, as guides on selecting plastics and processes as well as on how to keep up-to-date on important information and understand the economics of designing with plastics [1–200].*

Many different products can be designed using plastics and composites. They will take low to extremely high loads and operate in widely different environments, from highly corrosive ones to those involving electrical insulation. They challenge the designer with a combination of often unfamiliar and unique advantages, and limitations. By understanding the many different structures and properties as well as the design and fabrication capabilities, the designer can meet this challenge as demonstrated by the existence of the many different products made from plastics. They exist in all types of applications—underground, underwater, in the atmosphere, in outer space, in the office, and in the home.

Although plastics and composites may appear to some observers to be new, because the industry has an unlimited capacity to produce new plastics to meet new performance and processing requirements, plastics and composites have been used in no-load to extremely high-load situations for over a century. The ever-evolving technology does not mean that plastics and composites will automatically replace other materials. Each material (plastics, metals, wood, aluminum, and so forth) will, basically, be used in favorable cost-to-performance situations. As of the early 1980s, more plastics were used worldwide on a volumetric basis than any other materials except wood and concrete. Before the end of this century there will be on a weight basis more plastics used than the others, except wood and concrete.

*All references are listed in the References section in the back of the book.

2 DESIGNING WITH PLASTICS AND COMPOSITES: A HANDBOOK

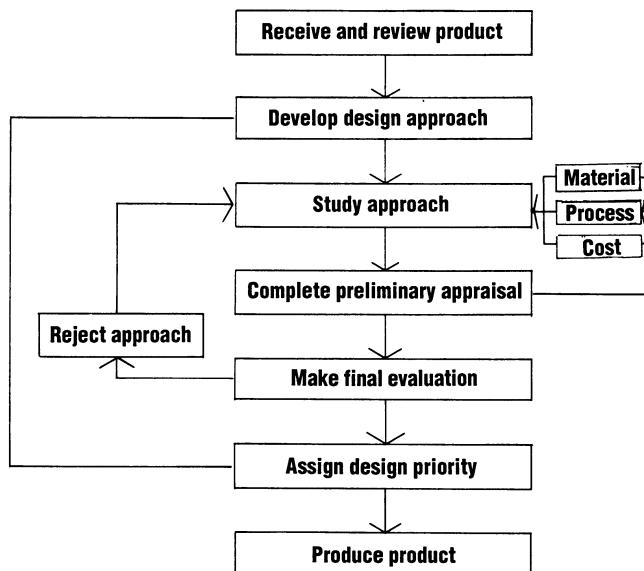


Figure 1-1. To be effective, the evaluation of new product ideas should proceed according to a logical step-to-step process, as shown.

With plastics and composites, to a greater extent than with other materials, an opportunity exists to optimize design by focusing on a material's composition and orientation as well as its structural-member geometry. There are also important interrelationships among shape, material selection (including reinforced plastics, elastomers, foams, and so forth), the consolidation of parts, manufacturing selection, and other factors that provide low cost-to-performance products. For the many applications that require only minimal mechanical performance, shaping through processing techniques can help overcome limitations such as low stiffness with commodity (lower cost) plastics. And when extremely high performance is required, reinforced plastics (RP), composites, and other engineering plastics are available. In this book the term *plastics* also refers to composites.

All processes fit into an overall scheme that requires the interaction and proper control of different operations. The *Follow All Opportunities* (FALLO) approach shown in Figure 1-2 can be used in any process by including the "blocks" that pertain to the fabricated product's requirements. (See Chapters 7 and 8 regarding basic processing and auxiliary—upstream and downstream—equipment.)

The FALLO approach has been used by many processors to produce parts at the lowest cost. Computer programs featuring this type of layout are available (see Chapter 10). The FALLO approach makes one aware that many steps are involved in processing, all of which must be coordinated. The specific process (injection, extrusion, blowmolding, thermoforming and so forth) is an important part of the overall scheme and should not be problematic. The process depends on several interrelated factors, such as designing a part to meet performance and manufacturing requirements at the lowest cost, specifying the plastics, and specifying the manufacturing process. To do so basically requires designing a tool (mold, die, and so forth) around the part, putting the proper-performance fabricating process around the tool, then setting up the necessary auxiliary equipment to interface in the complete fabricating line, and, finally, setting up completely integrated

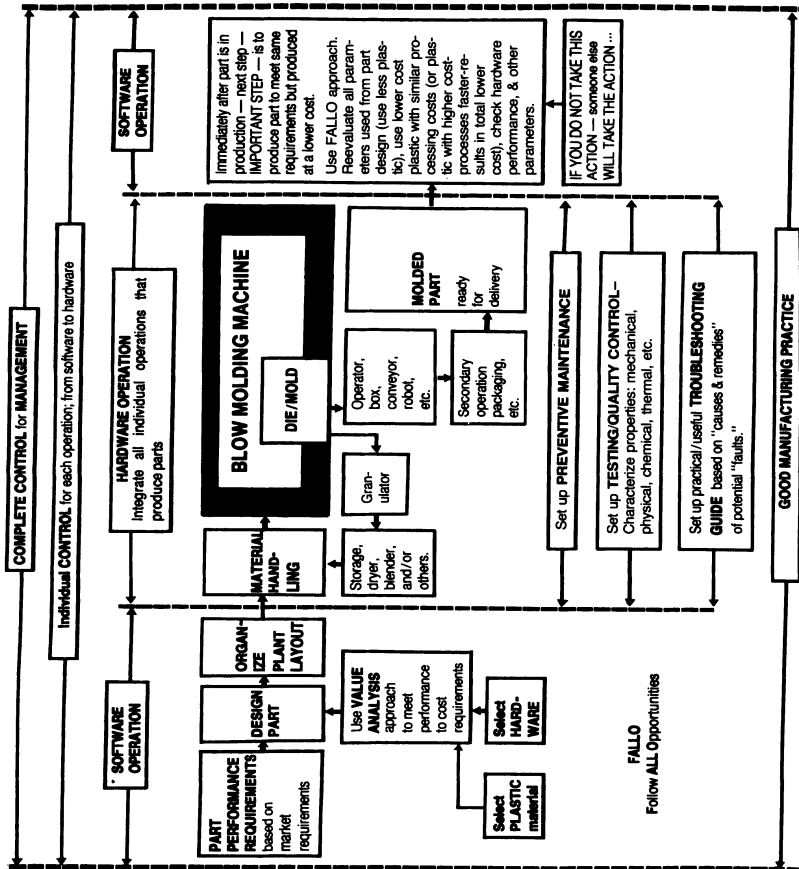
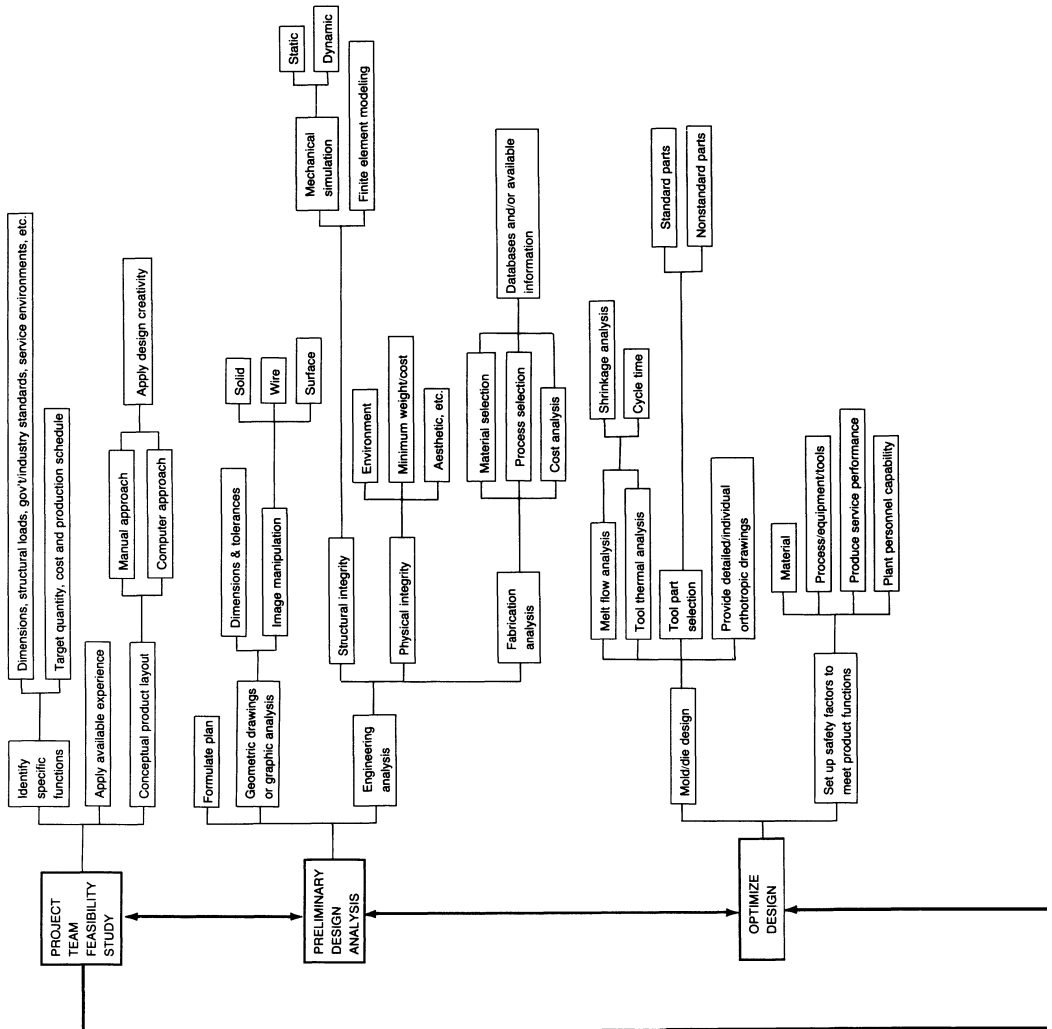


Figure 1-2. The example shown here for the complete blow-molding fabrication operation is also applicable to the other processes. This diagram shows the FALLO approach.



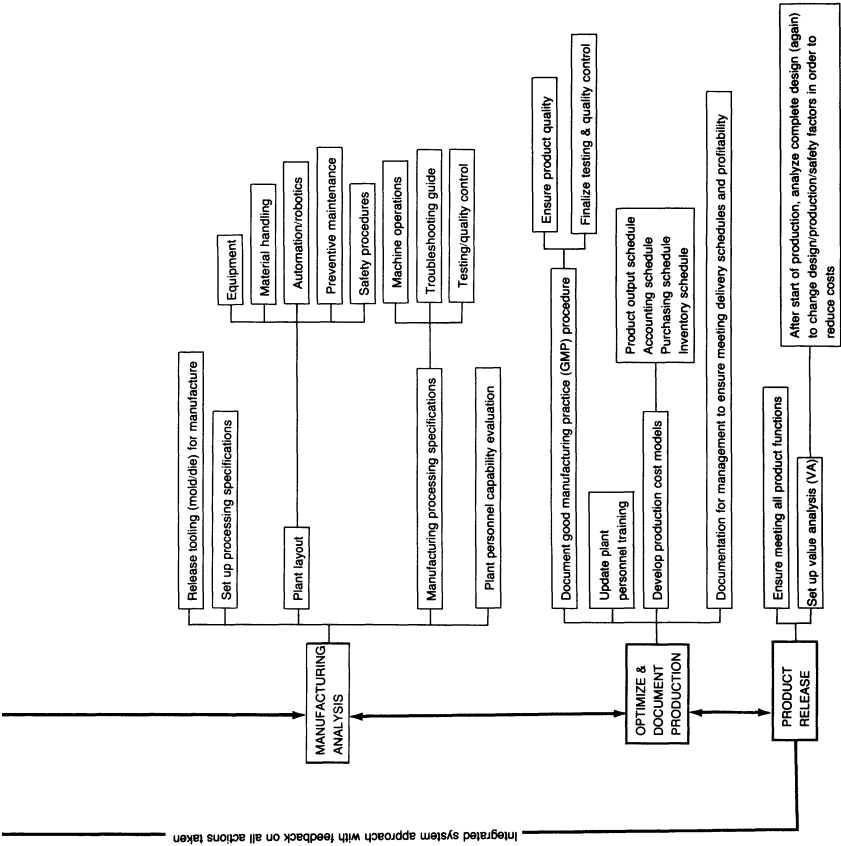


Figure 1-3. Flow diagram with feedback loops for product design using the FALLO approach (Follow ALL Opportunities). This flow diagram uses available CAD/CAE/CAM/CIM/CAT computer software programs. It provides the project team with the information necessary to aid in making final design decisions. All programs, particularly those with databases, should have the capability for continual updating and expansion.

6 DESIGNING WITH PLASTICS AND COMPOSITES: A HANDBOOK

controls to meet the goal of zero defects. The final step in the FALLO process is that of purchasing equipment as well as materials, then warehousing the material. This inter-relationship is different from that of most other materials, where the designer is usually limited to using specific prefabricated forms that are bonded, welded, bent, and so on.

Designing has never been easy in any material, particularly plastics, because there are so many. Plastics provide more types than all other materials put together—with about 45 families of plastics, many variations are available (see Figs. 1-4 and 1-5). Of the more than fifteen thousand different plastics, only a few hundred are used in large quantities. Unfortunately, many designers view plastics as a single material, because they are not aware of all the types available. Plastics are a family of materials each with its own special advantages. The major consideration for a designer is to analyze what is required as regards performance and develop a logical selection procedure from what is available (see Chapter 6).

The range of properties in plastics encompasses all types of environmental conditions, each with its own individual, yet broad, range of properties. These properties can take into consideration wear resistance, integral color, impact resistance, transparency, energy absorption, ductility, thermal and sound insulation, weight, and so forth (see Chapters 2, 3, 4, and 5). There is unfortunately no one plastic that can meet all maximum properties. Therefore, the designer has different options, such as developing a compromise, because many product requirements provide options, particularly if cost is of prime importance, or combining different plastics.

The combination approach permits using plastics that have different properties. They can just be stacked together, but with the available processes they can also be put together so that each material retains its individuality yet has a bond with the adjoining plastics. These processes of coinjection, coextrusion, and so on are reviewed in Chapter 7. Each of the individual plastics can provide such characteristics as wear resistance, being a barrier to water, an electrical conductor, and adding strength (Chapters 3–5). Recycled (solid waste) plastics can be sandwiched between other plastics. Plastics can also be combined with other materials such as aluminum, steel, and wood to provide specific properties (for example, PVC/wood window frames and plastic/aluminum-foil packaging

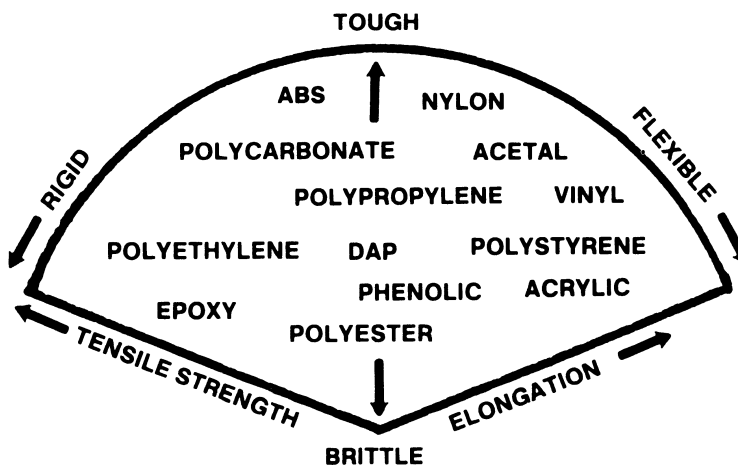


Figure 1-4. An example of the range of mechanical properties for plastics.

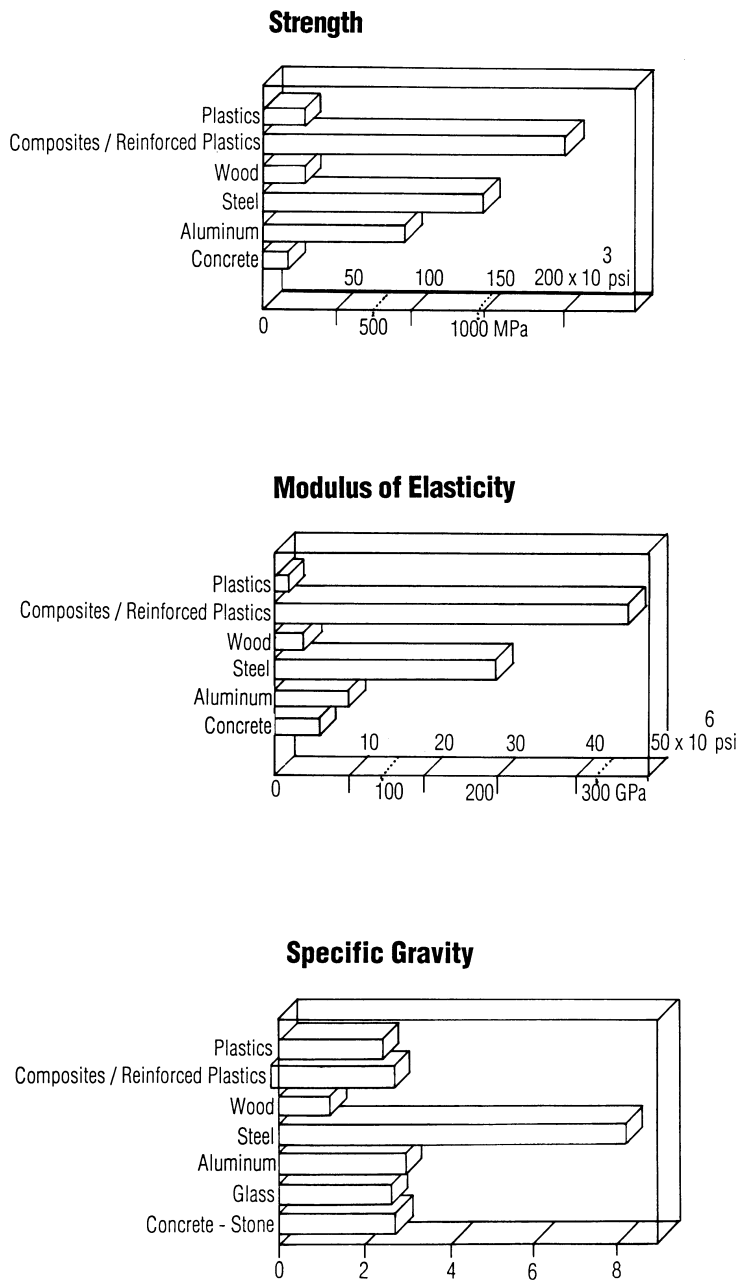
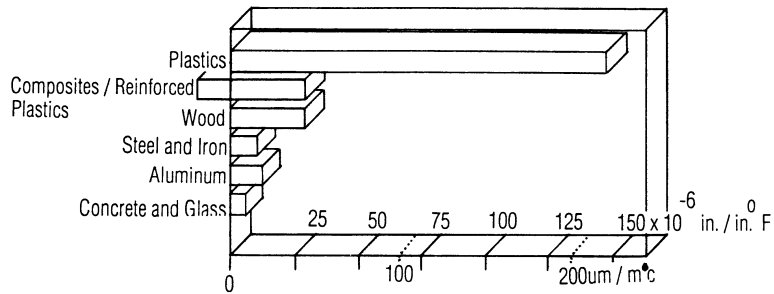
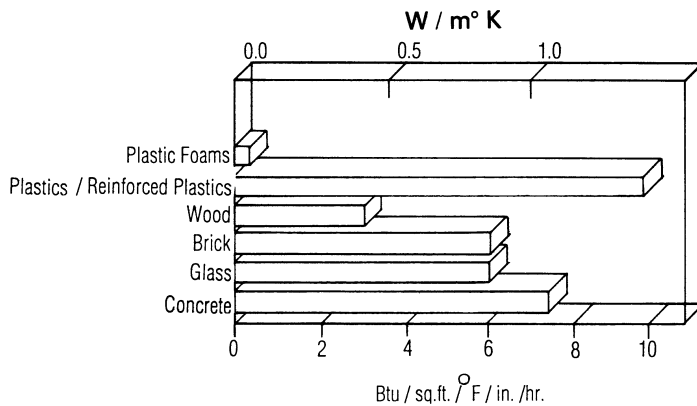


Figure 1-5. A general comparison of different materials.

Thermal Expansion



Thermal Conductivity



Maximum Continuous Service Temperature

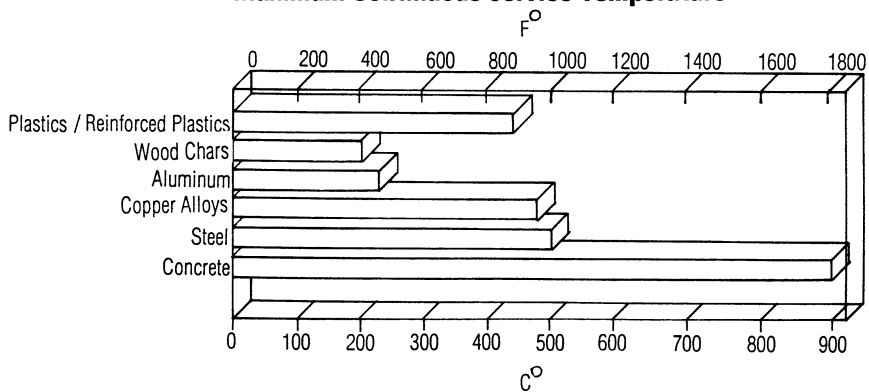


Figure 1-5. (Continued)

material). All combinations require that certain aspects of compatibility such as processing temperature and coefficient of expansion or contraction exist. (For a review of this area, see Chapter 7).

The designer can use conventional plastics that are available in sheet form, in l-beams, or other forms, as is common with many other materials. Although this approach with plastics has its place, the real advantage with plastics lies in the ability to process them to fit the design, particularly when it comes to complex shapes. Two or more parts—including mechanical and electrical connections, living hinges, colors, and snap fits—can be combined into one part (see Chapter 11).

Like other materials, all plastics can be destroyed by hot enough fires. Some burn readily, others slowly, others only with difficulty; still others do not support combustion after the removal of the flame. There are certain plastics used to withstand the reentry temperature of 2,500° F (1,370° C) that occurs when spacecraft return to the earth's atmosphere. (The time exposure is parts of a millisecond.) Different industry standards can be used to rate plastics at various degrees of combustibility. Plastics' behavior in fire depends upon the nature and scale of the fire as well as the surrounding conditions and how the products are designed. For example, the virtually all-plastic 35 mm slide projectors use a very hot electric bulb. When designed with a metal light and heat reflector and fan, no fire develops. Fire is a highly complex, variable phenomenon. Therefore, designing in this environment requires understanding all the variables, so that the proper plastics can be used (see Chapters 2–6).

The Design Process

The term *design* has many connotations, but it is essentially the process of devising a product to fulfill as completely as possible all the requirements of the end user, and, at the same time, satisfy the needs of the producer in terms of marketing and cost effectiveness (that is, return on investment). The efficient use of the available materials and production processes, including the all-important factor of tooling, should be the goal of every design effort (see Fig. 1-3).

A Changing World

It would be difficult to imagine the modern world without plastics. Today they are an integral part of everyone's life-style, with applications varying from commonplace domestic articles to sophisticated scientific and medical instruments. Nowadays designers and engineers readily turn to plastics. Exceptional progress has been made in this century worldwide in all markets. As a matter of fact, many of the technical wonders we take for granted would be impossible without versatile, economical plastics. Yet some who are not mindful of the many benefits of plastics still carry negative feelings about them. Some examples of their creative use follow.

1. *In recreation.* Because people everywhere tend to take their fun seriously, they spend freely on sports and recreational activities. The broad range of properties available from plastics has made them part of all types of sports and recreational equipment for land, water, and airborne activities. Roller-skate wheels are now abrasion- and wear-resistant polyurethane. Tennis rackets are molded from specially reinforced plastics and composites using glass, aramid, graphite, or other fibers. Skis are laminated

48 DESIGNING WITH PLASTICS AND COMPOSITES: A HANDBOOK

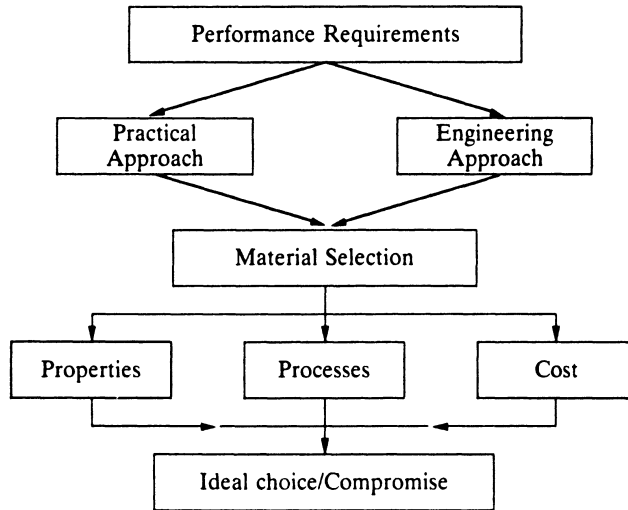


Figure 1-46. A simplified flow diagram for a design procedure.

The dimensioning of load-bearing products in many areas of design, except such highly sophisticated parts as those used in aircraft construction, is still often the result of tradition and empiricism, rather than being based on fact. This trial-and-error process is the usual practical approach. Without proper evaluation this approach could lead to failure or overengineering, which soon becomes costly. Good engineering design calls for extensive knowledge of materials' properties as expressed in tangible data. Only then is the designer in a position to predict the satisfactory functioning of a product.

It is not possible to obtain analytical mathematical solutions for many engineering designs that employ plastics, metals, ceramics, wood, and other materials. An analytical solution is a mathematical expression that provides guidelines or values for a desired unknown quantity at any location in a product. See the section on finite element analysis (FEA) in Chapter 6, for more information on analytical mathematical solutions.

Design Analysis

One factor that has done a great deal to harm the reputation of plastics is that in many cases designers and engineers have, after deciding tentatively to try to introduce plastics, then slavishly copied the metal part it was to replace. Too much emphasis cannot be given the general principle that if plastics are to be used for maximum advantage and with minimum risk of failure, it is essential to cast aside all preconceived notions of design in metals and treat plastics on their own merit as one would with any other material. A hard-and-fast rule to be followed by all intending to use plastics is to design *for* plastics. As an example, for the same-size cross-section the strength of conventional plastics (not the high-performance reinforced ones) is considerably less than that of most metals. The designer will thus find it necessary to increase thickness, introduce stiffening webs, and

possibly use design inserts of various types of threads to secure the proposed part. The process will in some instances also require modification to the shape of the equipment used to produce the part, or mean simplifying the fabricating process or reducing its cost (see Chapter 11).

It will become obvious that what is considered good design practice insofar as metals are concerned will not necessarily be good practice for processing plastics. It is advisable when in doubt to review this book, the referenced literature on the subject, or consult processing experts who know the limitations of plastics. By working in close cooperation with the plastics fabricator it is usually possible to arrive at a satisfactory compromise.

Almost all current methods of design analysis are based on models of material behavior that are relevant to traditional metallic materials, as for example elasticity and plastic yield (see Chapter 3). These principles are embodied in design formulas' design sheets or charts and in more modern techniques, such as computer-aided design (CAD) using finite element analysis. The design analyst is merely required to supply appropriate elastic or plastic constants for the material. Thus, traditional analysts can be expected to have little experience with plastics, a situation that is changing.

DESIGN SHAPE

Because the formability of plastics into almost any conceivable shape is one of its design advantages, it is important for designers to understand what can be done in this medium. Shape, which can be almost infinitely varied in the early design stages, allows a given weight of materials to provide a whole spectrum of strength properties, especially in the most desirable areas of stiffness and resistance to bending.

In all materials, elementary mechanical theory demonstrates that some shapes resist deformation from external loads or residual stresses in processing better than do others. This phenomenon stems from the basic physical fact that deformation in beam and sheet sections depends upon the product of modulus (E) and the second moment of inertia (I), commonly expressed as EI . The physical part performance can be changed by varying the moment of inertia or the modulus or both (see Chapter 3).

Thickening plastic panels to meet stiffness requirements is an expensive use of any plastic (or other material, for that matter) because inefficiently large quantities of the material are used, and increased heating and cooling times raise the cost of fabrication.

Adding more material to a plastic structural component does not always make it stronger. Unless the reinforcing ribs are added in the correctly engineered proportions, some of the additional material may be placed so that it creates high stresses, actually decreasing the loads that cause yielding or fracture (see Fig. 1-47). Lengthy equations for the moment of inertia and for deflection and stress are normally required to determine the effect of ribs on stress. However, nondimensional curves have been developed to allow quick determination of proper rib proportions, and a corresponding program for a pocket calculator or computer will allow for obtaining greater precision when required (see Chapters 3–5).

With potential limitations of rib reinforcements, the use of sandwich structures made of foam, with or without facings or other cores like honeycombing, corrugation, and so forth can be used to offer high stiffness-to-weight ratios. These proportions will have a wide range of depths for improving the second moment of inertia and torsional stiffness. And integral skin-molding techniques have the additional advantage of leaving the surface of the panel effectively unfoamed.

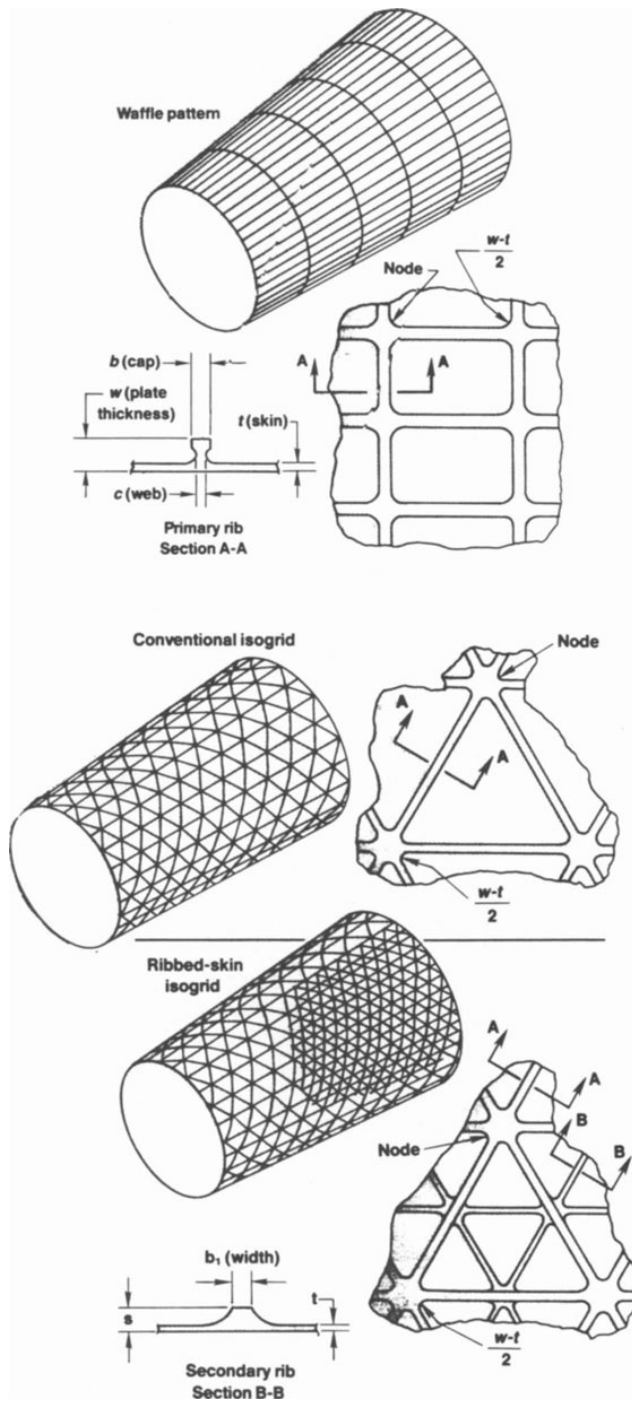


Figure 1-47. Thin-skinned structures with integral ribbing to carry edge loads.

50

In principle, the sandwich structure is similar to the I-beam shape in which the facings correspond to the flanges and the cores to the webs. The facings resist axial loads and provide the moment-resisting couple; the core stabilizes the facings against buckling or wrinkling under axial compression and provides resistance to shear in bending. To obtain maximum performance, facings are commonly made of reinforced plastics. Cores are usually of foamed plastics, unreinforced or reinforced plastic honeycomb, phenolic impregnated kraft paper, or balsa wood.

SUCCESS BY DESIGN

A skilled designer blends a knowledge of materials, an understanding of manufacturing processes, and imagination into successful new designs. Recognizing the limits of design with traditional materials is the first step in exploring the possibilities for innovative design with relatively new materials. What is important when analyzing designs is to incorporate ergonomics and empathy, to result in a product that truly answers the user's needs.

With designing there has always been the need to meet engineering, styling, and performance requirements at the lowest cost. To some there may appear to be a new era where ergonomics is concerned, but this is not true. What is always new is that there are continually easier methods on the horizon to simplify and meet all the specific requirements of a design. Some designers operate by creating only the stylish outer appearance, allowing basic engineers to work within that outside envelope. Perhaps this is all that is needed to be successful, but a more in-depth approach will work better. Beginning with a thorough understanding of the user's needs and keeping an eye toward ease of manufacture and repair, designers should also work from the inside out. The envelope that eventually emerges will then be a logical and aesthetic answer to the design challenge (see Fig. 1-48).

With new plastics and processes always becoming available, the design challenge becomes easier, even when taking today's solid-waste problem into account. Today's plastics and processes, as reviewed throughout this book, allow designers to incorporate and interrelate all the aspects of success. In products such as electronics, medical devices, transportation controls (as for aircraft, cars, and boats), and many others where user-friendly design is required, it has to be obvious to all that plastics play an important role.

Responsibilities

The responsibilities of designers encompass all aspects of design. Although functional design is of paramount importance, a design is not complete if it is functional but cannot easily be manufactured, or functional but not dependable, or if it has a good appearance but poor reliability. Designers have a broad responsibility to produce designs that meet all the objectives of function, durability, appearance, and low cost. They should not contend that something is now designed and it is now the manufacturing engineer's job to figure out how to make it at a reasonable cost. The functional design and the production design are too closely interrelated to be handled separately.

Product designers must consider the conditions under which fabrication will take place, because these conditions affect part performance and cost (Chapter 7). Such factors as production quantity, labor, and material cost are vital. Designers should also visualize how each part is to be fabricated. If they do not or cannot, their designs may not be satisfactory or even feasible from a production standpoint. One purpose of this book is

52 DESIGNING WITH PLASTICS AND COMPOSITES: A HANDBOOK

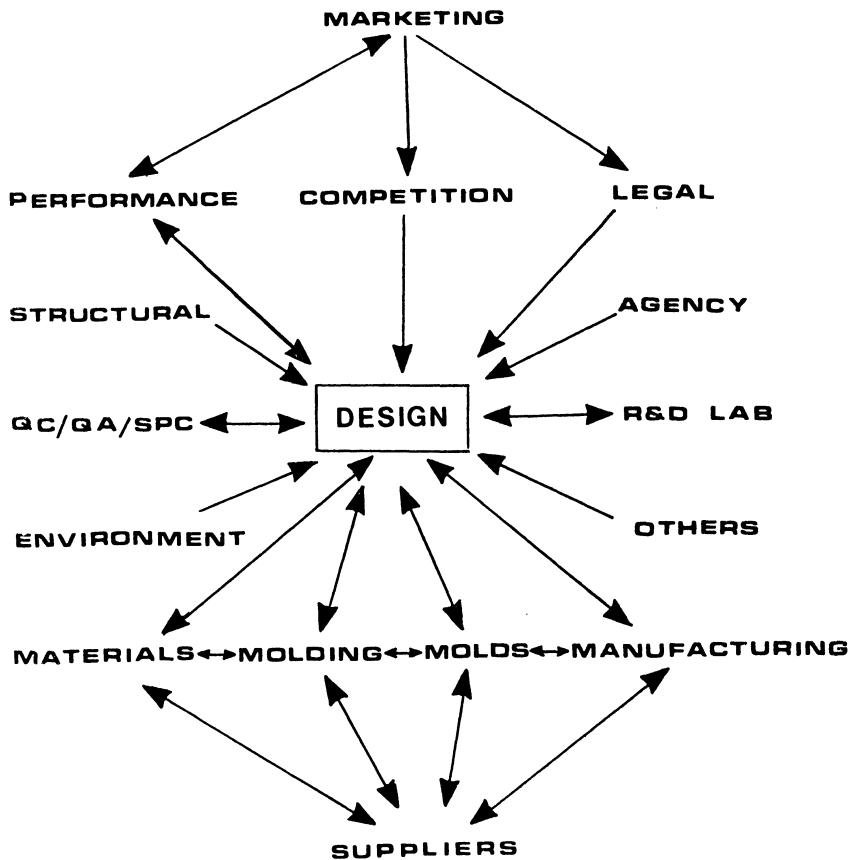


Figure 1-48. The overall design challenge.

to give designers sufficient information about manufacturing processes so that they can design intelligently from a productivity standpoint.

Ethics

Although there is no substitute for individual action based on a firm philosophical and ethical foundation, designers have developed guidelines for professional conduct based on the experience of many of them who have had to wrestle with troublesome ethical questions and situations previously. These guidelines can be found in the published codes of ethics for designers and engineers of a number of industry and technical societies.

COMPUTERS IN DESIGN

The use of computers in design and related fields is widespread and will continue to expand. It is increasingly important for designers to keep up to date continually with the nature and prospects of computer technologies. For example, plastics databases, accessible

through computers, provide product designers with property data and information on materials and processes.

To keep material selection accessible via computer terminal and a modem, the design database maintains graphic data on thermal expansion, specific heat, tensile stress and strain, creep, fatigue, programs for doing fast approximations of the stiffening effects of rib geometry, educational information and design assistance, and more (see Chapters 3–6, 10, and the Appendix).

Computer-Aided Design

Computer-aided design (CAD) is the process of solving design problems with the aid of computers. This function includes the computer generation and modification of graphic images on a video display, printing these images as hard copy using a printer or plotter, analyzing the design data, and electronic storage and retrieval of design information. Many CAD systems perform these functions in an integrated fashion that can increase the designer's productivity manyfold.

It is important to recognize that the computer does not change the nature of the design process; it is simply a tool to improve efficiency and productivity. It is appropriate to view the designer and the CAD system together as a design team, with the designer providing knowledge, creativity, and control and the computer accurate, easily modifiable graphics and the capacity to perform complex design analysis at great speeds and store and recall design information. Occasionally, the computer can augment or replace many of the designer's other tools, but it is important to remember that this ability does not change the fundamental role of the designer.

Computer-Aided Design Drafting

Computer-aided design drafting (CADD), a part of CAD, is the computer-assisted generation of working drawings and other documents. The CADD user generates graphics by interactive communication with the computer. The graphics are displayed on a video terminal and can be converted into hard copy by a printer or plotter.

Computer-Aided Manufacturing

Computer-aided manufacturing (CAM) describes a system that can take a CAD product, devise its essential production steps, and electronically communicate this information to manufacturing equipment such as robots. A CAD/CAM system offers many potential advantages over traditional manufacturing systems, including the need for less design effort through the use of CAD and CAD databases, more efficient material use, reduced lead time, greater accuracy, and improved inventory functions.

Computer-Integrated Manufacturing

Computer-integrated manufacturing (CIM) is the coordination of all stages of manufacturing, which enables the manufacturers to custom design products efficiently and economically, by a computer or a system of computers.

54 DESIGNING WITH PLASTICS AND COMPOSITES: A HANDBOOK

Computer-Aided Testing

The computer-aiding testing (CAT) addition to computer-aided activities involves the testing that takes place in all stages of product development (see Chapter 7). The advantage of CAT is that the output of sensors measuring the characteristics of the prototype or finished product can manipulate the product model to improve its accuracy or identify design modifications needed. In this way testing integrates design and fabrication into an ongoing, self-correcting development process.

DESIGN PROCEDURE

There are certain elements common to all successful designers: knowledge of their particular design field, experience, creativity, a knowledge of the materials and processes of manufacturing, and the ability to represent a design to others. It is in this ability to represent a design that all the elements come together. A design may be represented by hand-drawn renderings or be generated by computer, with instructions provided by the designer. Regardless of the mode of representation, designing is personally satisfying because of the creativity involved in it.

All designers must have a thorough training in graphics. Without it a designer must fail, because as the design conception proceeds the designer's thinking must be recorded in the form of sketches and drawings. Design drawings will often be augmented and supported by mathematical data and diagrams, including computer data.

The Safety Factor

A factor of safety (FS) or safety factor (SF) is used to provide for the uncertainties associated with any design. In addition to the basic uncertainties of graphic design, a designer may also have to consider additional uncertainties:

1. *Variations in material properties.* Because no two plastic (or steel, for that matter) melts are exactly alike—some may have inclusions and so on—the strength properties given in materials tables are usually average values. If the value stated is a manufacturer's value, it probably is the minimum value, which can significantly reduce or eliminate its uncertainty.
2. *Effect of size in stating material strength properties.* Property tables, unless otherwise stated for plastics, metals, and so on, list strength values based on a specified size, yet larger components generally fail at a lower stress than a similar smaller component made of the same material (Chapter 3).
3. *Type of loading.* A simple static load is relatively easy to recognize, but there are cases that fail between impact and suddenly applied loads. One thus takes into account infrequently applied fatigue loading mixed with some shock loads, as for example cams, links, or feeding devices (Chapter 5).
4. *Effect of processes.* The fabricating operations for plastics, steel, glass, and so forth may, and usually do, introduce stress concentrations and residual stresses (Chapter 7).
5. *Overall concern for human safety.* All design must consider safety of the user who may be near or in contact with the product. Unexpected overloads or other situations may cause breakage and considerable bodily harm.

In order to take uncertainties into account in design, there is the safety factor or the so-called “factor of ignorance.” (See Chapter 5 regarding SF.) Many designers do use the SF, but improper use of it may result in needless waste or the cost of extra material, or even physical or operational failure. Thus, one must define what one means when using the SF. In some cases the SF is stipulated by code or contract requirements.

Predicting Performance

Avoiding structural failure can depend in part on the ability to predict performance for all types of materials (plastics, metals, glass, and so on). Design engineers have developed sophisticated computer methods for calculating stresses in complex structures using different materials. These computational methods have replaced the oversimplified models of materials behavior relied upon previously. The result is early comprehensive analysis of the effects of temperature, loading rate, environment, and material defects on structural reliability. This information is supported by stress–strain behavior data collected in actual materials evaluations (see Chapters 3–5).

With computers the finite element method (FEA) has greatly enhanced the capability of the structural analyst to calculate displacement, strain, and stress values in complicated plastic structures subjected to arbitrary loading conditions. In its most fundamental form, FEA is limited to static, linear elastic analyses. However, there are advanced finite element computer programs that can treat highly nonlinear dynamic problems efficiently. Important features of these programs include their ability to handle sliding interfaces between contacting bodies and the ability to model elastic–plastic material properties. These program features have made possible the analysis of impact problems that only a few years ago had to be handled with very approximate techniques. Finite element techniques have made these analyses much more precise, resulting in better and more optimum designs (see Chapter 5).

Nondestructive testing (NDT) is used to assess a component or structure during its operational lifetime. Radiography, ultrasonics, eddy currents, acoustic emissions, and other methods are used to detect and monitor flaws that develop during operation (see Chapter 9).

The selection of the evaluation method(s) depends on the specific type of plastic, the type of flaw to be detected, the environment of the evaluation, the effectiveness of the evaluation method, the size of the structure, and the economic consequences of structural failure. Conventional evaluation methods are often adequate for baseline and acceptance inspections. However, there are increasing demands for more accurate characterization of the size and shape of defects that may require advanced techniques and procedures and involve the use of several methods.

INTERRELATING PRODUCT-RESIN-PROCESS PERFORMANCES

In order to understand potential problems and solutions of design, it is helpful to consider the relationships of machine capabilities, plastics processing variables, and part performance (see Fig. 1-49). A distinction has to be made here between machine conditions and processing variables. For example, machine conditions include the operating temperature and pressure, mold and die temperature, machine output rate, and so on. Processing variables are more specific, such as the melt condition in the mold or die, the flow rate versus temperature, and so on (see Chapter 7).

Interrelate Product - Resin - Process

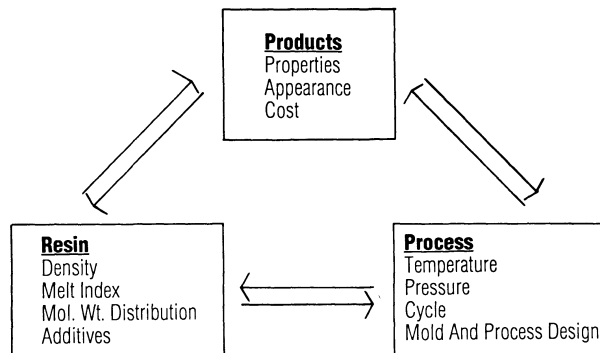


Figure 1-49. Interrelating product-resin-process performance.

A distinction between machine conditions and processing variables must be made in order to avoid mistakes in using cause-effect relationships to advantage. It is the processing variables, properly defined and measured, not necessarily the machine settings, that can be correlated with part performance. There was a time when designers took little interest in the processing of the parts they had designed. They simply sent the drawings to the processor in another department or company and expected perfect parts to emerge, but design and processing are now so interrelated that this separation should not exist if products are to be consistently successful.

Those familiar with processing can detect and correct visible problems or readily measure factors such as color, surface conditions, and dimensions. However, less-apparent property changes are another matter. These may not show up until the parts are in service, unless extensive testing and quality control are used (see Chapters 9 and 11).

Advantages and Disadvantages of Plastics

As a construction material, plastics provide practically unlimited benefits to the design of products, but unfortunately no one specific plastic exhibits all these positive characteristics. The successful application of their strengths and an understanding of their weaknesses will allow designers and engineers to produce useful products. This book reviews the advantages and disadvantages of plastics. There is a wide variation in properties among the fifteen thousand commercially available materials classified as plastics. They now represent an important, highly versatile group of engineering materials. Like steel, wood, and other materials, specific groups of plastics can be characterized as having certain properties. As with other materials, for every advantage cited, a corresponding disadvantage can probably be found (see Fig. 1-50).

In general, most plastics can easily be fabricated into all shapes and sizes. As reviewed, if desired they can have highly intricate shapes held to tight tolerances by using processes suitable for either limited or mass production. Many plastics can be worked using common shop techniques. Other generalizations include the fact that many consider plastics to be of low cost. In fact, some are so expensive that their use is limited to the most sophisticated technology and applications. Regardless, if the cost of materials appears to be too high

FUNDAMENTALS OF DESIGNING WITH PLASTICS AND COMPOSITES 57

for an application, a look at the processing method to be used may show that it could be less expensive, based on the material-to-processing costs. Many designers overlook this aspect. Plastics are typically not as strong or as stiff as metals, and they are prone to dimensional changes, especially under load or heat. Successful designs take these conditions into account when they influence design requirements (see Chapter 3). As will be seen, there are plastics that are stronger or stiffer than metals, and there are those that also have exceptional dimensional stability.

Highly favorable conditions such as less density, good thermal insulation, a high degree of mechanical dampening, high resistance to corrosion and chemical attack, and exceptional electric resistance exist for certain plastics. There are of course those that will deteriorate when exposed to sunlight, weather, or ultraviolet light, but then there are those that resist such deterioration.

No matter what the material may be, there is always room for improvement, whether it be in plastics, metals, wood, design parameters, testing procedures, or any other category. Designers are generally most familiar with metals and wood and their behavior under load and varying conditions of temperature and environment. For those designing in metals and the other materials that have been used for centuries there is extensive literature available, and since very few changes occur one can easily enter the field of designing with these materials and refer to the handbooks that tell one what to do.

As an example, for room-temperature applications most metals can be considered to be truly elastic. When stresses beyond the yield point are permitted in the design, permanent deformation is considered to be a function only of applied load and can be determined directly from the stress-strain diagram. The behavior of most plastics is much more dependent on the time of application of the load, the past history of loading, the current and past temperature cycles, and environmental conditions. Ignorance of these complexities has resulted in the appearance on the market of many plastic products that were improperly designed. Fortunately, product performance has been greatly improved as the amount of technical information on the mechanical properties of plastics has increased in the last century, particularly since the 1940s. More importantly, designers have become more familiar with the behavior of plastics rather than just pronouncing that one cannot design with plastics, something that has never been true (see Chapters 3-5).

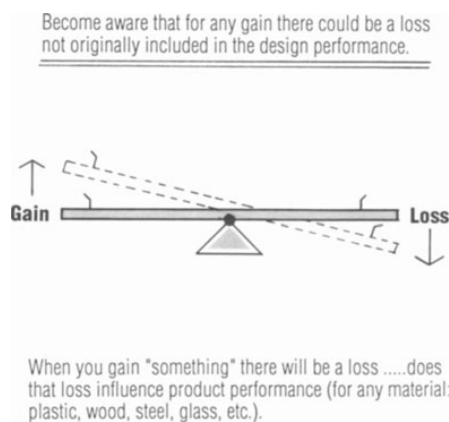


Figure 1-50. For any gain, there could be a loss not originally included in design performance.

58 DESIGNING WITH PLASTICS AND COMPOSITES: A HANDBOOK

Energy to Manufacture

To produce and process plastics requires less energy than practically any other material (see Fig. 1-51). In contrast, glass requires much more energy than any of the materials listed in Figure 1-51.

Solid Waste

Only about 7 percent, by weight, of the solid waste produced is plastics. Incinerating, recycling, landfill, and other methods are used to handle the worldwide plastics (and other materials) waste problems. Incineration of plastics produces a high energy content. For example, polystyrene has nearly twice the energy content of coal, without its ensuing problems of ash, acid rain pollution, or harmful emissions. Plastics are just one of many materials that produce solid waste, and, as with other materials, there are good and bad disposal solutions.

In the United States, about 20 percent or 81,000 t (90,000 tons) of plastic (polyethylene terephthalate; PET) soft-drink bottles are being recycled. The high-density polyethylene (HDPE) milk bottles recycled amount to 36,000 t (40,000 tons) per year. See Chapter 12 for more details on the waste problem.

Cost

It is a popular misconception that plastics are cheap materials—they are not. On a weight basis most plastics are more expensive than steel, and only slightly less so than aluminum (see Fig. 1-52). It should be remembered that it is a bad design practice to select materials on the basis of cost per unit weight rather than volume. By far the real advantage to using plastics to produce low-cost products is the low processing cost, as discussed previously. Figures 1-53 to 1-55 show different factors involving costs.

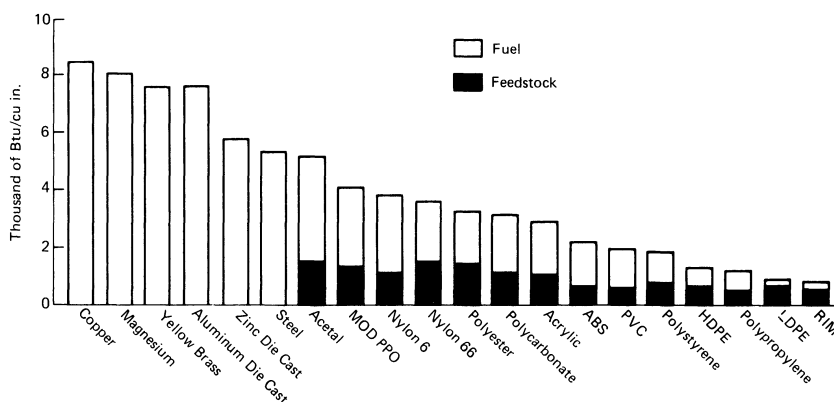


Figure 1-51. Energy requirements for different materials.

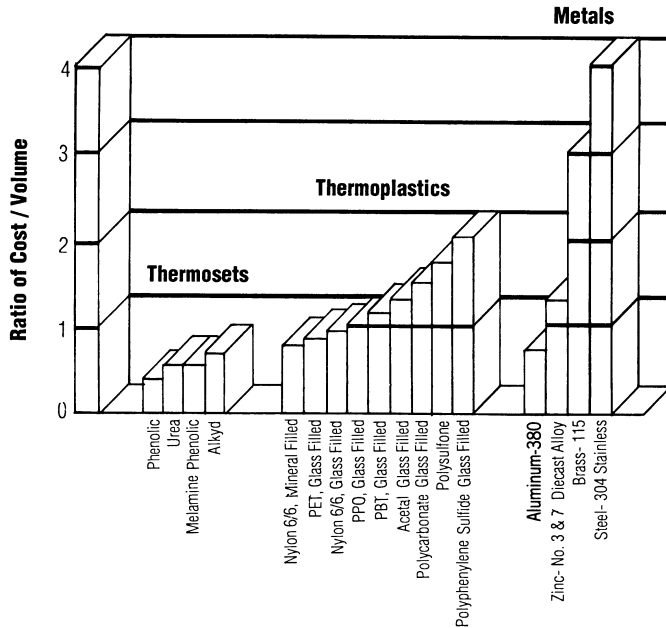


Figure 1-52. A general cost comparison, based on volume, for a general classification of materials.

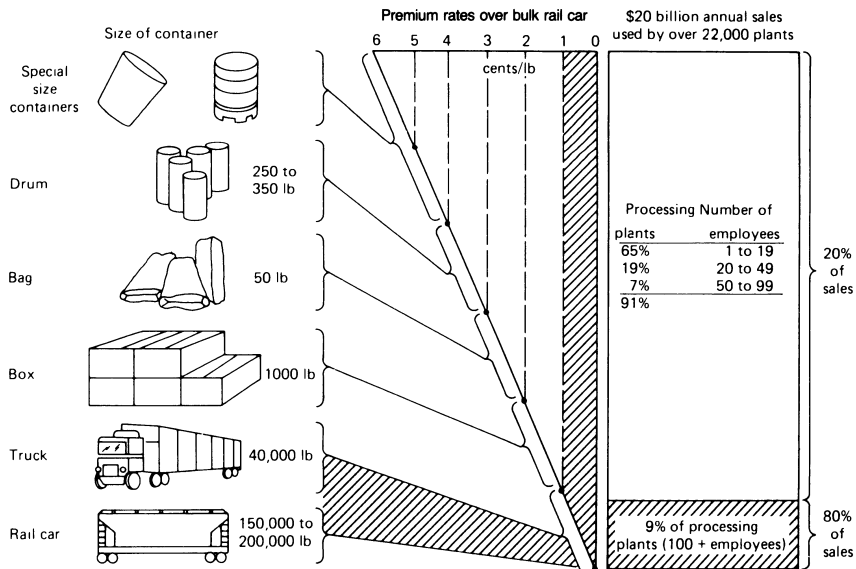


Figure 1-53. Estimated plastics dollar purchases by plant size and size of containers.

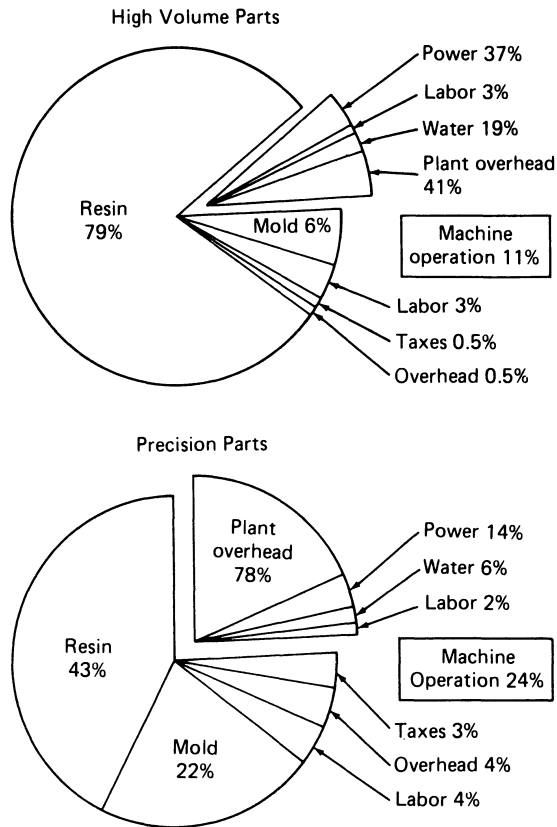


Figure 1-54. Share of cost to injection mold high-volume parts and precision parts.

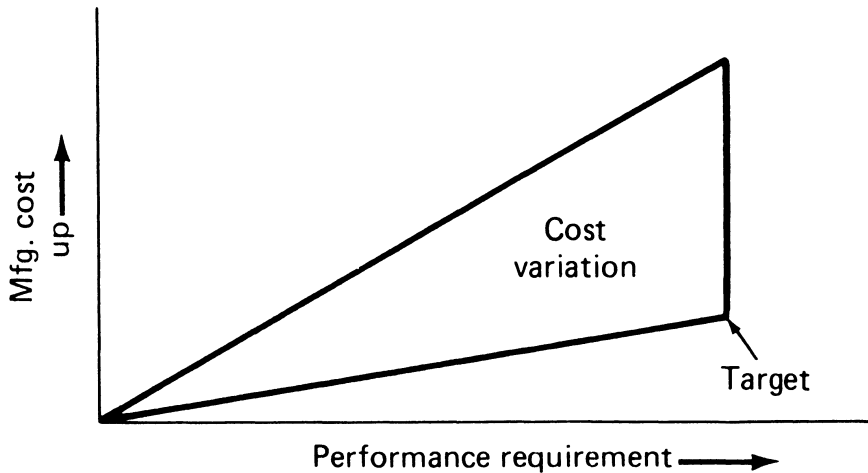


Figure 1-55. The influence of manufacturing costs and performance requirements on product cost.

Chapter 7

THE PROCESSING OF PLASTICS

The various processes discussed in this chapter are used to fabricate all types and shapes of plastic products, ranging from household convenience packages to electronic devices and many others—including the strongest products in the world, used in space vehicles, aircraft, building structures, and so on. Proper process selection depends upon the nature and requirements of the plastic, the properties desired in the final product, the cost of the process, its speed, and the product volume. (Remember that a plastic may also be called a polymer or a resin.) Some materials can be used with many kinds of processes, but others require a specific or specialized machine (see Fig. 7-1). Plastics consumption by process is given in Table 7-1. Numerous fabrication process variables play an important role and can markedly influence a product's aesthetics, performance, and cost.

This review provides information on the effects on performance and cost of changing individual variables during processing, including upstream and downstream auxiliary equipment. Many of these variables and their behaviors are the same in the different processes, as they all relate to temperature, time, and pressure. This chapter contains information applicable to all processes characterized by certain common variables or behaviors, such as plastic melt flow, heat controls, and so forth. It is essential to recognize that for any change in a processing operation there can be advantages and disadvantages. The old rule still holds: for every action there is a reaction. A gain in one area must not be allowed to cause a loss in another; changes must be made that will not be damaging in any respect.

All processes fit into an overall scheme that requires interaction and proper control of its different operations. An example is shown in Figure 7-1, where a complete block diagram pertains to a process. This FALLO (*Follow ALL Opportunities*) approach can be used in any process by including those blocks that pertain to the fabricated product's requirements.

Knowledge of all the processing methods, including their capabilities and limitations, is useful to a designer in deciding whether a given part can be fabricated and if so by which process. Certain processes require placing high operating pressures on plastics, such as those used in injection molding, where pressures may range from 13.8 to 206.9 Pa (2,000 to 30,000 psi). Because of these pressures and the fact that three-dimensional parts are molded, injection molding is the most complex process, but it is easily controlled. Lower pressures are used in extrusion and compression, ranging from 1.4 to 69 Pa (200 to 10,000 psi), and some processes, such as thermoforming and casting, operate at relatively little pressure. Basically, with the higher pressures it is possible to develop

589

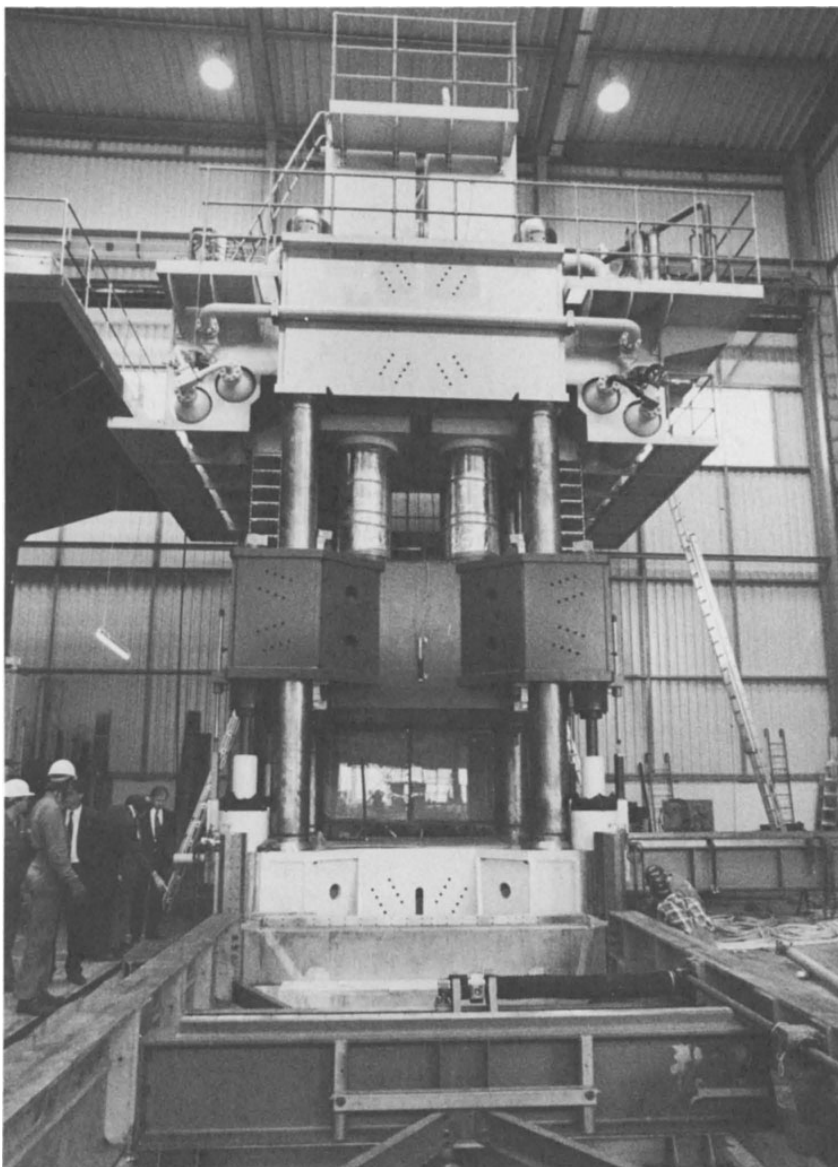


Figure 7-1. Alpha I, the centerpiece multipurpose machine for GE Plastics' Polymer Processing Development Center in Pittsfield, Mass. is in the center of a facility with a dozen more different processing machines. This one-of-a-kind multipurpose machine measuring 75 ft. long $\times$ 50 ft. wide $\times$ 55 ft. tall can produce parts up to six feet square. It is the world's first machine to combine more than seven processes, including injection molding, flow molding, tamping, coinjection molding, gas injection molding, compression molding, flow forming, side-by-side, and proprietary processes.

590

abello@ssjr.com

Table 7-1. Plastics Consumption by Processes

Material	Percent by Weight
Extrusion	36
Injection	32
Blowing	10
Calendering	6
Coating	5
Compression	3
Powder	2
Others	6

Approximate values, U.S. and worldwide.

tighter dimensional tolerances with higher mechanical performance, but there is also a tendency to develop undesirable stresses (orientations) if the processes are not properly understood or controlled. A major exception is reinforced plastics processing at low or contact pressures. Regardless of the process used, its proper control will maximize performance and minimize undesirable process characteristics.

Practically all processing machines can provide useful products with relative ease, and certain machines have the capability of manufacturing products to very tight dimensions and performances. The coordination of plastic and machine facilitates these processes. This interfacing of product and process requires continual updating because of continuing new developments in manufacturing operations. The information presented throughout this book should make past, present, and future developments understandable in a wide range of applications [1–14, 62–69, 537–673].

Most products are designed to fit processes of proven reliability and consistent production. Various options may exist for processing different shapes, sizes, and weights (see Table 7-2). Parameters that will help one to select the right options are 1) setting up specific performance requirements; 2) evaluating materials' requirements and their processing capabilities; 3) designing parts on the basis of material and processing characteristics, considering part complexity and size (see Fig. 7-2) as well as a product and process cost comparison (see Table 7-3); 4) designing and manufacturing tools (molds, dies, etc.) to permit ease of processing; 5) setting up the complete line, including auxiliary equipment (Fig. 7-1 and Chapter 8); 6) testing and providing quality control, from delivery of the plastics through production to the product (see Chapter 9); and 7) interfacing all these parameters by using logic and experience or obtaining a required update on technology.

Polymers usually are obtained in the form of granules, powder, pellets, and liquids. Processing mostly involves their physical change (thermoplastics), though in some cases chemical reactions occur (thermosets) (Chapter 2). A variety of processes are used. One group consists of the extrusion processes (pipe, sheet, profiles, etc.). A second group takes extrusion and in certain cases injection molding through an additional processing stage (blow molding, blown film, quenched film, etc.). A third group consists of injection and compression molding (different shapes and sizes), and a fourth group includes various other processes such as thermoforming, calendering, and rotational molding.

The common features of these groups are 1) mixing, melting, and plasticizing; 2) melt transporting and shaping; 3) drawing and blowing; and 4) finishing. Mixing, melting, and plasticizing produce a plasticized melt, usually made in a screw (extruder or injection).

Table 7-2. Examples of Competitive Processes versus Different Products

	Injection Molding	Extrusion	Blow Molding	Thermoforming	Reaction Injection Molding	Rotational Molding	Compression and Transfer Molding	Matched Mold, Spray-up
Bottles, necked containers, etc.	2, A	—	1	2, A	—	2	—	2
Cups, trays, open containers, etc.	1	—	—	1	1	—	1	2
Tanks, drums, large hollow shapes, etc.	—	—	1	2, A	—	1	—	2
Caps, covers, closures, etc.	1	—	—	2	2	—	1	—
Hoods, housings, auto parts, etc.	1	—	2	2	2	—	1	1
Complex shapes, thickness changes, etc.	1	—	—	—	—	—	1	2
Linear shapes, pipe, profiles, etc.	2, B	1	—	—	—	—	2, B	—
Sheets, panels, laminates, etc.	—	1, C	—	—	—	—	2	2

1. Prime process.

2. Secondary process.

A. Combine two or more parts with ultrasonics, adhesives, etc.

B. Short sections can be molded.

C. Also calendaring process.

Table 7-3. Cost Comparison of Plastic Products and Different Processes
 (Cost Factor × Material Cost = Purchased Cost of Product)

Process	Cost Factor	
	Overall	Average
Blow molding	1 ¹ / ₁₆ to 4	1 ¹ / ₈ to 2
Calendering	1 ¹ / ₂ to 5	2 ¹ / ₂ to 3 ¹ / ₂
Casting	1 ¹ / ₂ to 3	2 to 3
Centrifugal casting	1 ¹ / ₂ to 4	2 to 4
Coating	1 ¹ / ₂ to 5	2 to 4
Cold pressure molding	1 ¹ / ₂ to 5	2 to 4
Compression molding	1 ³ / ₈ to 10	1 ¹ / ₂ to 4
Encapsulation	2 to 8	3 to 4
Extrusion forming	1 ¹ / ₁₆ to 5	1 ¹ / ₈ to 2
Filament winding	5 to 10	6 to 8
Injection molding	1 ¹ / ₈ to 3	1 ³ / ₁₆ to 2
Laminating	2 to 5	3 to 4
Match-die molding	2 to 5	3 to 4
Pultrusion	2 to 4	2 to 3 ¹ / ₂
Rotational molding	1 ¹ / ₄ to 5	1 ¹ / ₂ to 3
Slush molding	1 ¹ / ₂ to 4	2 to 3
Thermoforming	2 to 10	3 to 5
Transfer molding	1 ¹ / ₂ to 5	1 ³ / ₄ to 3
Wet lay-up	1 ¹ / ₂ to 6	2 to 4

Melt transporting and shaping involve applying pressure to the hot melt in order to move it through a die or into a mold. The drawing and blowing technique stretches the melt to produce orientation of the different shapes (blow molding, forming, etc.). The final feature of processing, finishing, is the usual solidification of the melt.

Many product designs are inherently limited by the economics of the process that must be used to make them. For example, TSs cannot be blow molded, and to date they have limited extrusion possibilities. Many hollow parts, particularly very large ones, may be produced more economically by the rotational process than by blow molding. The need for a low quantity of parts may eliminate certain molding processes and indicate the use of casting or others. The extrusion process has fewer problems with TPs than does injection

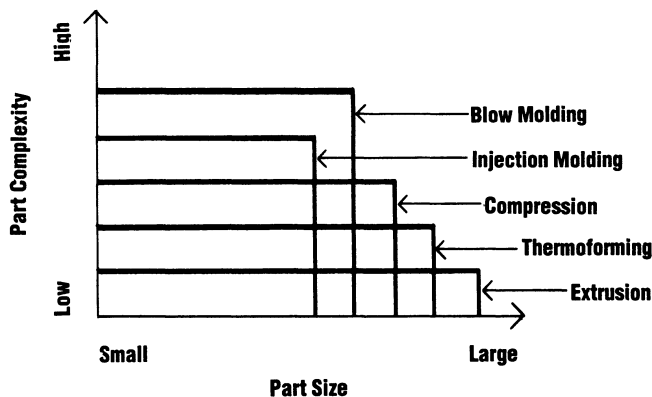


Figure 7-2. A design guide for processing characteristics in regard to size and complexity.

594 DESIGNING WITH PLASTICS AND COMPOSITES: A HANDBOOK

molding but has greater problems in dimensional control and shape. However, as the plastic leaves the extrusion die, it can be relatively stress-free. It is drawn in size and passed through downstream equipment from the extruder to form its shape as it is cooled, usually by air and/or water. The dimensional control and the die shape required to achieve the desired part shape are usually solved by trial-and-error settings, with the more experience one has in the specific plastic and equipment being used meaning the less trial time needed.

Other analyses can be made. Compression and injection molds, which are expensive and relatively limited in size, are employed when the production volume required is great enough to justify the molds' costs and the sizes are sufficient to fit available equipment's limitations. Extrusion produces relatively uniform profiles at unlimited lengths. Casting is not limited by pressure requirements and large sheets, for example, can be produced. Calendered sheets are limited in their width by the width of the material's rolls, but are unlimited in length. Vacuum forming is not greatly limited by pressure, although even a small vacuum distributed over a large area can build up an appreciable load. Blow molding is limited by equipment that is feasible for the mold sizes. Rotational molding can produce relatively large parts.

The tendency of injection molding and extrusion to align long chain molecules in the direction of flow results in their having markedly greater strength in that direction than at right angles. With an extruded pressure pipe, for example, its major strength could be in the axial/machine direction when the major stresses in the pipe wall are circumferential. With the proper processing-condition controls, the directional properties required can be obtained. If in an injection mold the plastic flows in from several gates, the melts must unite or weld where they meet. This process may not be complete, however, especially with filled plastics, so the welds may be points of weakness. Careful gating with proper processing control can allow welds to occur where stresses will be minimal.

The nature of the process may have profound influence on such properties as Izod impact strength. Figure 7-3 compares the impact strengths of three PP formulations that were processed either by injection or compression molding. In this example the IM process resulted in a drastic reduction of impact strength over that offered by the CM. This situation can be reversed by varying the processing conditions.

Certain products are most economically produced by fabricating them with conventional machining out of compression-molded blocks, laminates or extruded sheets, rods or tubes. It may be advantageous to design a product for the postmolding assembly of inserts, to gain the benefit of fully automatic molding and automatic insert installation, even though inserts could greatly increase the cost of TP parts.

The choice of molder and fabricator places no limits on a design. There is a way to make a part if the projected values justify the price; any job can be done "at a price." The real limiting factors are tool-design considerations, material shrinkage, subsequent assembly or finishing operations, dimensional tolerances, allowances, undercuts, insert inclusions, parting lines, fragile sections, the production rate or cycle time (see Fig. 7-4), and the selling price.

Applying the following principles, applicable to virtually all manufacturing processes, will aid the designer in specifying parts that can be produced at minimum cost: 1) maintaining simplicity; 2) using standard materials and components; 3) specifying liberal tolerances; 4) employing the most processable plastics; 5) collaborating with manufacturing people; 6) avoiding secondary operations; 7) designing what is appropriate to the expected level of production; 8) utilizing special process characteristics; and 9) avoiding processing restrictions.

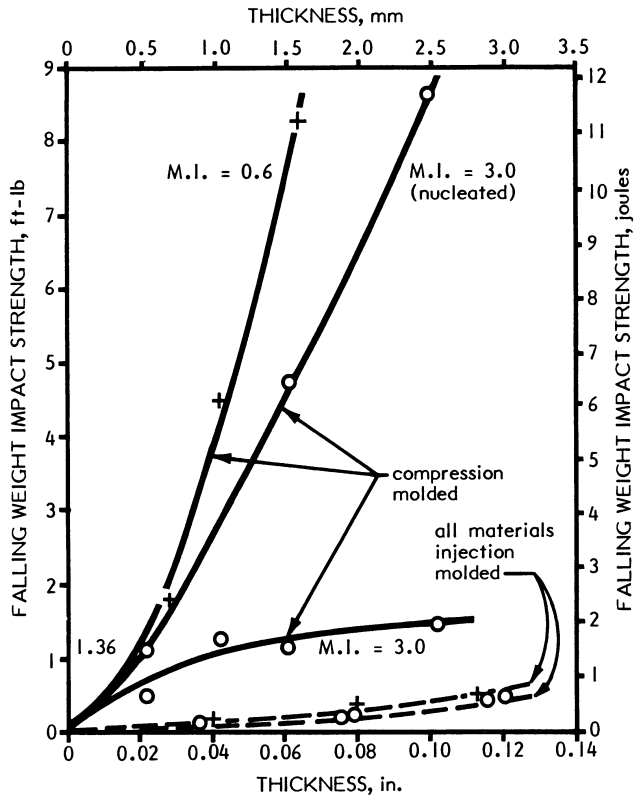


Figure 7-3. An example of the effect of processing conditions on Izod impact strength for PP with different melt index flow behaviors.

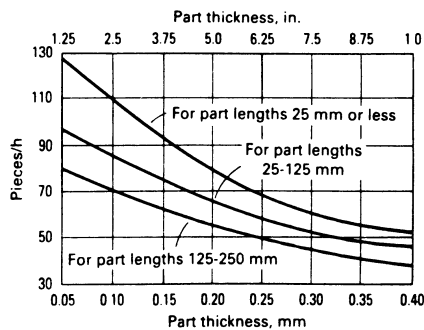


Figure 7-4. An example of cycle time during the injection molding of TPs as a function of part thickness.

595

610 DESIGNING WITH PLASTICS AND COMPOSITES: A HANDBOOK

Establishing initial design tolerances is often done on an arbitrary, uninformed basis. If the initial estimated tolerance proves too great, a lower-shrink plastic could be used to reduce the shrinkage range. However, if the key dimension was across a main parting line, the tooling could be redesigned to eliminate the condition and consequently reduce variation from tool construction. Even with all these data processed by a computer, estimating tolerances is difficult if they are not properly interrelated with the highly dependent factors of the part and tooling designs.

INJECTION MOLDING

The injection-molding (IM) process is greatly preferred by designers because the manufacture of parts in complex shapes and three dimensions can be more accurately controlled and predicted with IM than with other processes. As its method of operation is much more complex than others, IM requires a thorough understanding. Figures 7-15 and 7-16 show schematics of the load profile and the molding cycle that highlight the way in which the melt is plasticized (softened) and forced into the mold, the clamping system for opening and closing the mold under pressure; the type of mold used, and the machine controls [1, 2, 10, 12, 576–600].

Plastic moves from the hopper onto the feeding portion of the reciprocating extruder screw. The flights of the rotating screw cause the material to move through a heated extruder barrel where it softens (is made fluid) so that it can be fed into the shot chamber (front of screw). This motion generates pressure (usually 50–300 psi [0.35–2.07 MPa]), which causes the screw to retract. When the preset limit switch (or a position transducer, on newer machines), is reached the shot size is met and the screw stops rotating. At a preset time the screw acts as a ram to push the melt into the mold. Injection takes place

Table 7-8. An Example of IM Processing Temperatures used with Heat Resistance for Engineering TP*

Polymer	Type	T_g deg. F (°C)	Processing Temperature, deg. F (°C)
Polyetheretherketone (PEEK)	Semicrystalline	290 (143)	650 (343)
Polyphenylene sulfide (PPS)	Semicrystalline	185 (85)	630 (332)
Polyaryleneketone	Semicrystalline	400 (204)	700–780 (371–416)
Polyarylene sulfide	Amorphous	410 (210)	625–650 (329–343)
Polyetherimide (PEI)	Amorphous	Varies	Varies
		450 (232)	575–650 (302–343)
		545 (285)	650–700 (343–371)
Polyarylether	Amorphous	476 (247)	650 (343)
Polyethersulfone (PES)	Amorphous	510 (266)	575 (302)
Polyamide-imide (PAI)	Amorphous	470 (243)	650 (343)
Polyimide	Pseudothermoplastic	480 (249)	680 (360)
		482 (250)	660 (349)
		536 (280)	660 (349)
		536 (280)	660 (349)

*Typical commodity TPs use about 400° to 550°F (204° to 288°C).

at high pressure (up to 30,000 psi [207 MPa] melt pressure in the nozzle). Adequate clamping pressure must be used to eliminate mold opening (flushing). The melt pressure within the mold cavity ranges from 1 to 15 tons/sq. in. and is dependent on the plastic's rheology/flow behavior (see Chapter 2).

Time, pressure, and temperature controls indicate whether the performance requirements of a molded part are being met. The time factors include the rate of injection, duration of ram pressure, time of cooling, time of plastication, and screw RPM (see Fig. 7-16). Pressure factors are injection high and low pressure, back pressure on the extruder screw, and pressure loss before the plastic enters the cavity, which can be caused by a variety of restrictions in the mold. The temperature factors are mold (cavity and core), barrel, and nozzle temperatures, as well as the melt temperature from back pressure, screw speed, frictional heat, and so on.

The large number of variables summarized in Figure 7-8 will cause part changes if not properly controlled. The basic settings for these variables are provided by the plastic's producer: the injection barrel temperature, melt temperature (see Table 7-8), the cavity melt pressure, and so on. However, the final settings are determined by the processor on a specific machine and mold.

Even though most of the literature on processing specifically identifies or refers to thermoplastics (TPs), as in this book, some thermosets (TSs) are used (TS polyesters, phenolics, epoxy, etc.). The TPs reach maximum heat prior to entering "cool" mold cavities, whereas the TSs reach their maximum temperature in "hot" molds.

Productivity

Productivity is directly related to cycle time. There usually is considerable common knowledge about a part's geometry and process conditions that will provide a minimum cycle time. Practices such as using thinner wall sections, cold or hot runners for TPs or hot or cold ones for TSs (see Figs. 7-17 and 7-18), narrow sprues and runners, the optimal size and location of coolant (or heat) channels, and lower melt or mold heat, will when possible decrease the solidification time.

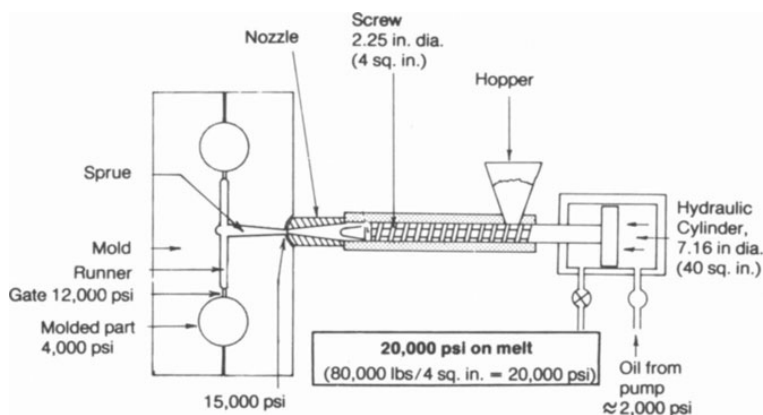


Figure 7-15. An example of pressure loading on plastic melt during injection molding (see Appendix B for English to metric conversions).

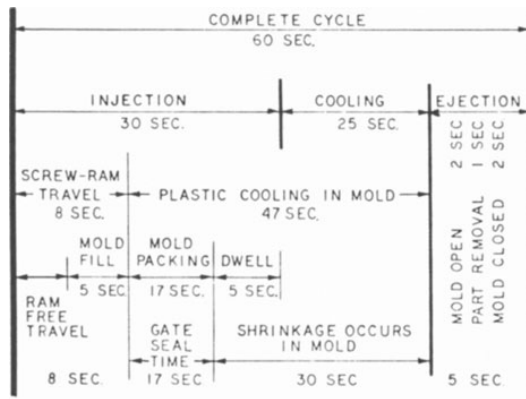


Figure 7-16. An example of injection molding cycle processing thermoplastics.

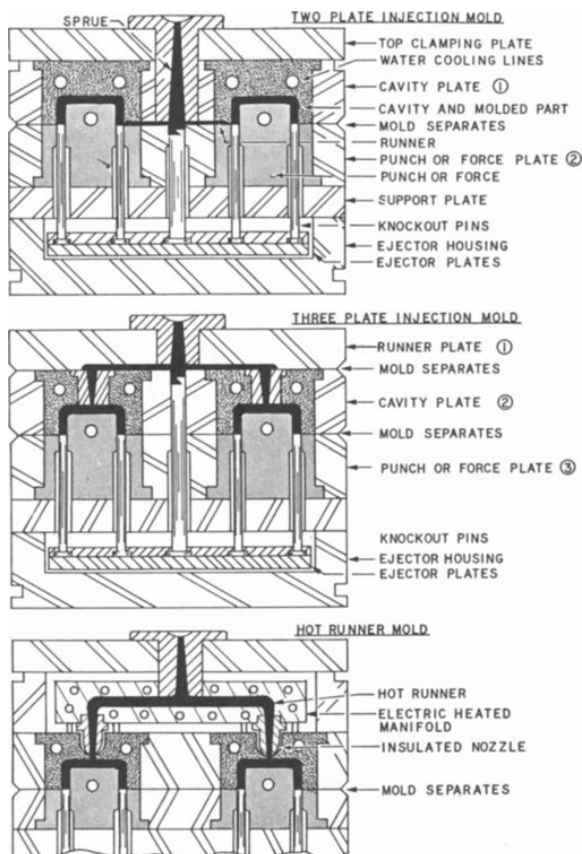


Figure 7-17. Types of injection molds.

612

Numerous factors affect the elapsed time required to eject a part, as different plastics can have dramatically different melt behaviors. Many of these influences are poorly, if at all, understood. Some critical ones are the coefficient of expansion, melt rheology, thermal diffusivity, and the thermomechanical spectrum. Although the usual and important ways to optimize time are based on part design and process conditions, it can be shown that additional and significant decreases occur by using modified molding compounds via additives, alloying ratios, molecular weight distribution, and so on.

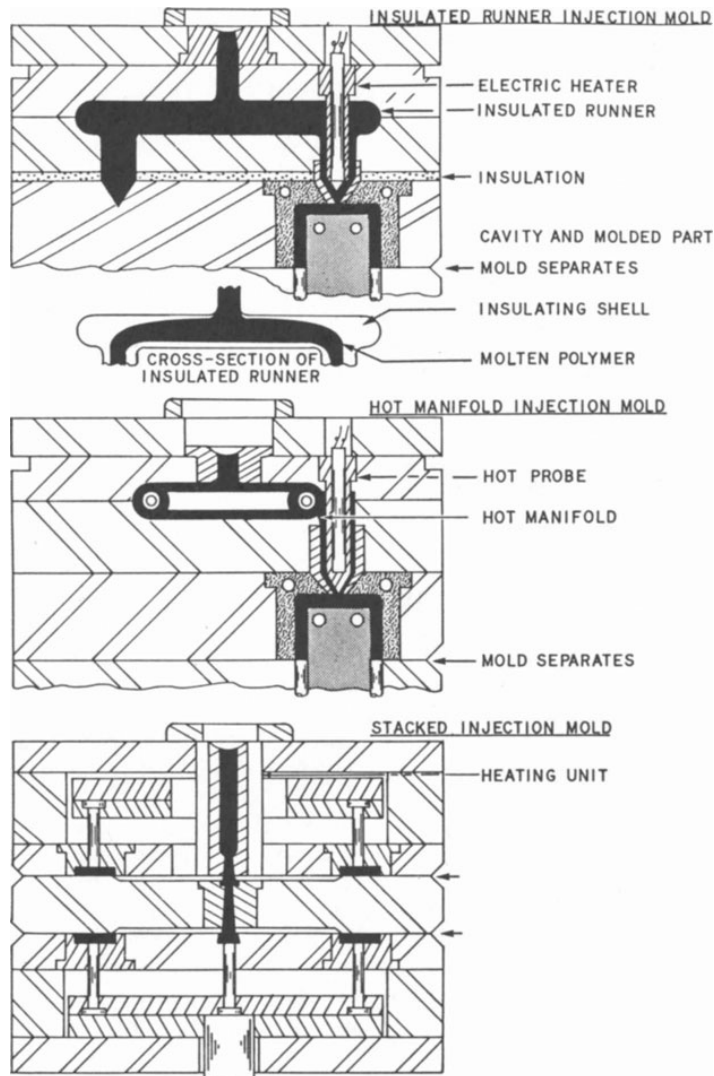


Figure 7-18. Three further types of injection molds.

Mathematical models of part geometry and melt flow within the mold cavity, which are available for mold design, are useful tools for optimizing cycle times. They allow a wide variety of plastics materials and process parameters to be evaluated in a convenient, cost-effective manner [10]. CAD and engineering algorithms offer a continually higher level of sophistication in determining the best heat distribution throughout the part. In actual practice, parts are not ejected according to a measurement of their internal or wall temperatures. Ejection times are set through secondary characteristics of part heat, such as the ability of the part to withstand the forces of ejection, the occurrence of sink marks or other thermal warpage, and the part's overall gloss or appearance. The prediction of sink marks appears amenable to CAD/CAE calculation. Part appearance still plays a larger role in the art of IM.

Screw Design

With practically all machines, only the cylinder temperature is directly controlled. The actual heat of the melt, within the screw and as it is ejected from the nozzle, can vary considerably, depending on the efficiency of the screw design and the method of operation. The factors affecting melt heat include the time the plastic remains in the cylinder; the internal surface heating area of the cylinder and the screw, per volume of material being heated; the thermal conductivity of the cylinder, screw, and plastic; the heat differential between the cylinder and the melt; and the amount of melt turbulence in the cylinder. In designing the screw, some balance must be maintained between the need to provide adequate time for heat exposure and to maximize output most economically.

In general, heat-transfer problems have led screw designers to concentrate on making screws more efficient as heat-transfer devices. As a result, the internal design and performance of screws will vary considerably to accommodate the different plastics used. Most machines are single, constant-pitch, metering-type screws to handle the majority of plastics.

Air Entrapment

Air can be entrapped in the melt during processing when plastic pellets or flakes are melted in a normal air environment, as in a plasticating extrusion process or injection barrel, compression mold, casting form, or spray system and the air cannot escape. Generally, the melt is subject to a compression load, or even a vacuum, which causes a release of air, but in some cases the air is trapped. If the air entrapment is acceptable, no further action is required. However, it is usually unacceptable, for reasons of both performance and aesthetics.

Changing the initial melt temperature in either direction may solve the problem. With a barrel and screw, it is important to study the effects of temperature changes. Another approach is to increase the pressure in processes that use process controls. The particle size, melt shape, and the melt delivery system may have to be changed or better controlled. A vacuum hopper feed system may be useful. With screw plasticators, changes in screw design may be helpful. Usually, a vented barrel will solve the problem.

The presence of bubbles could be due to air alone or moisture, plastic surface agents or volatiles, degradation, or the use of contaminated regrind. With molds such as those used for injection, compression, casting, or reaction injection, air or moisture in the mold cavity will be the culprit. So the first step to resolving a bubble or air problem is to be sure what problem exists. A logical troubleshooting approach can be used.

Shot-to-Shot Variation

During IM, shot-to-shot variations can occur. The major causes of inconsistency are worn nonreturn valves, bad seating of a nonreturn valve, a broken valve ring, a worn barrel in the valve area, or a poor heat profile. To identify the cause, follow a logical procedure. Any problem caused by the valve will cause the screw to rotate in the reverse direction during injection. To locate the trouble, pull and inspect the valve and check the OD of the ring for wear. The inspector looks for a broken valve stud (caused by cold startup when the screw is full of plastic), bad seating of the ring or ball (the angles of the ring ID and the seat must be different, in order to ensure proper shutoff action at the ID of the ring), and a broken ring. Check the dimensions of the valve and compare them with those determined before using the machine.

Purging

Purging has always been a necessary evil, consuming substantial amounts of materials, labor, and machine time, all nonproductive. In IM it is sometimes necessary to run hundreds of pounds of resin to clean out the last traces of a dark color before changing to a lighter one. Sometimes there is no choice but to pull the screw for a thorough cleaning. Although there are few generally accepted rules on how to purge, the following tips should be considered: 1) try to follow less viscous with more viscous resins; 2) try to follow a lighter color with a darker color of resin; 3) maintain the equipment; 4) keep the materials-handling equipment clean; and 5) use an intermediate resin to bridge the temperature gap (such as that encountered in going from acetal to nylon), and use a PS as a purge.

Molds

A mold must be considered one of the most important pieces of production equipment in the plant. It is a controllable complex device (see Fig. 7-19) that must be an efficient heat exchanger. If not properly designed, handled, and maintained, it will not be an efficient operating device. Hot melt, under pressure, moves rapidly through the mold. Water or some other medium circulates in the mold to remove (for TPs) or add (for TSs) heat. Air is released from cavities to eliminate melt burning or voids in the part. All kinds of actions operate, including sliders and unscrewing devices [2, 10, 11]. Parts like knockout pins as well as air are ejected at the proper time. These basic operations in turn require all kinds of interactions, including such parameters as fill-time, hold pressure, and other variables, as shown in Figures 7-8 and 7-9.

Each of the plastics used has special distinctive properties. Some are abrasive or corrosive; others require very tight heat control and pressure. Settings that work for one resin probably will not work for another, or a machine change to a duplicate will probably require different settings. Shrinkage requires special attention. Crystalline resins shrink more than amorphous ones (see Chapter 2). Differential shrinkage can cause warpage. With tight part tolerances it is necessary to leave more, rather than less, steel in the mold so that corrections requiring metal "cutting" can correlate processing with tolerances.

CAD and CAE programs are available that can aid in mold design and in setting up the complete process [11]. These programs are concerned with melt flow to part solidification and the meeting of performance requirements. Many different factors are incorporated, including heat transfer, thermal conductivity, thermal expansion, the coefficients of friction, machine and mold operating setup, and so on.

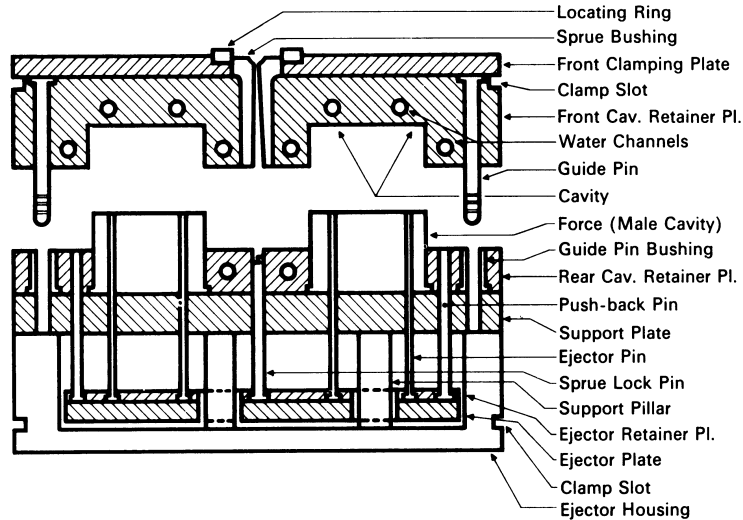


Figure 7-19. A two-part standard mold.

Molding Variables versus Performance

There are variables during molding that influence part performance. The information presented here shows how melt flow variables behave to influence products' properties. A flow analysis can be made to aid designers and moldmakers in obtaining a good mold. Of paramount importance is controlling the fill pattern of the molding so that parts can be produced reliably and economically. A good fill pattern for a molding is one that is usually unidirectional in nature, thus giving rise to a unidirectional and consistent molecular orientation in the molded product. This approach helps avoid warpage problems caused by a differential orientation, an effect best demonstrated by the warpage that occurs in thin center-gated disks. In this case all the radials are oriented parallel to the flow direction, with the circumferences transverse to the flow direction. The difference in the amounts of shrinkage manifests itself in terms of warpage of the disk.

In order to achieve a controlled fill pattern, the mold designer must select the number and location of gates that will result in the desired pattern. Flow analysis can help by allowing the designer to try multiple options for gate locations and evaluate the impact on the molding process. This analysis often can be conducted with the product designer to achieve the best balance of gate locations for cosmetic impact and molding considerations. Figures 7-20 through 7-29 show various flow patterns, orientation patterns, and property performances (see also Chapter 3) [11].

In the practical world of mold design, there are many instances where design trade-offs must be made in order to achieve a successful overall design. While naturally balanced runner systems are certainly desirable, they may lead to problems in mold cooling or increased cost due to excessive runner-to-part weights (see Fig. 7-17). Additionally, there are many cases such as parts requiring multiple gates or family molds in which balanced runners cannot be used. Flow analysis tools allow successful designs of runners to balance for pressure, temperature, or a combination of both.

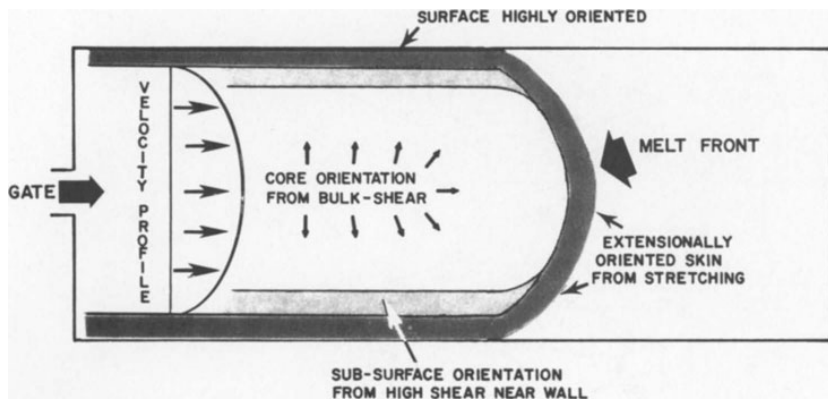


Figure 7-20. Cavity melt flow looking at a part's thickness.

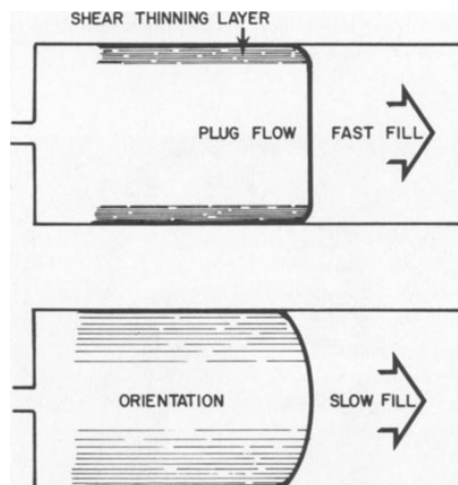


Figure 7-21. The effects of different fill rates.

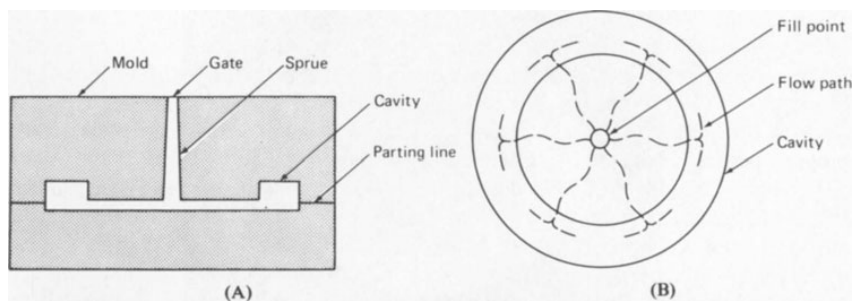


Figure 7-22. Plastic melt does not flow uniformly through the diaphragm of plate mold (A) in the compensating phase, but spreads in a branching pattern (B).

617

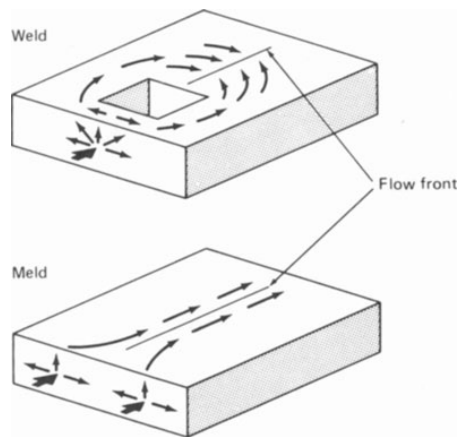


Figure 7-23. Flow paths are determined by part shape and gate location. Flow fronts that meet head on will weld together, forming a weld line. Parallel fronts tend to blend, however, producing a less distinct weld line but a stronger bond.

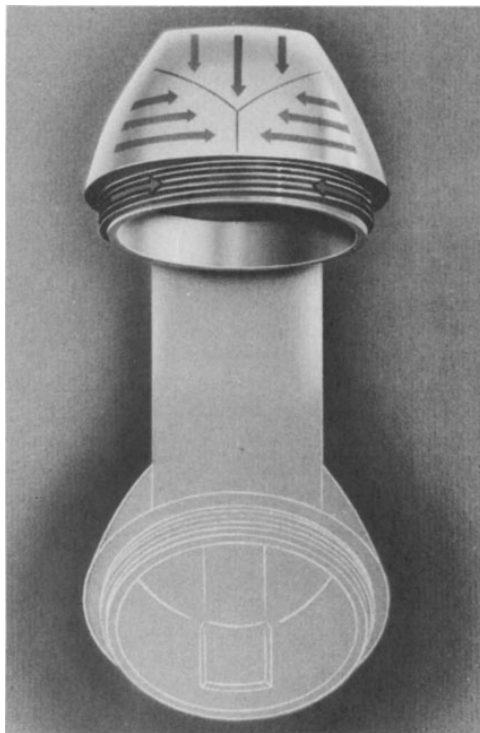


Figure 7-24. Example of flow lines or weld lines in a telephone handset where the gate was located at the top-center part of the handle.

618

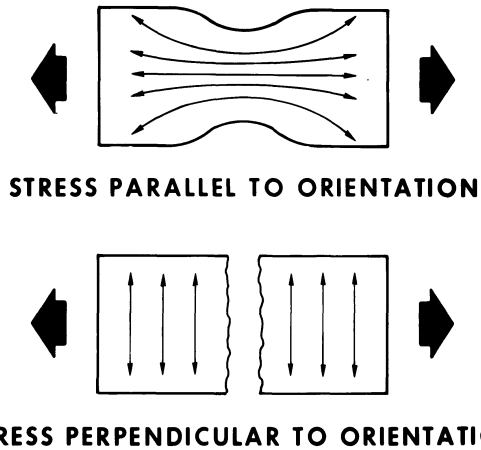


Figure 7-25. The effect of orientation on strength: the highest tensile strength is in the direction parallel to the orientation.

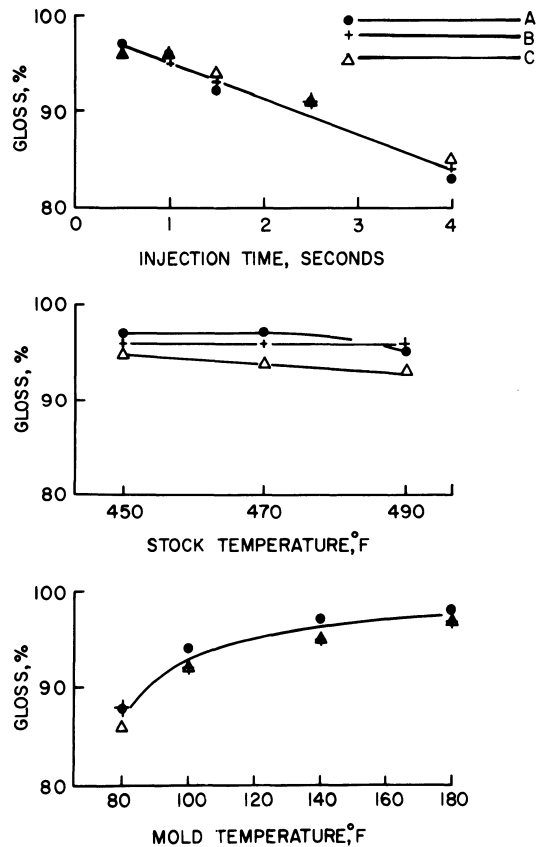


Figure 7-26. The effect of molding conditions on the gloss of an ABS plastic.

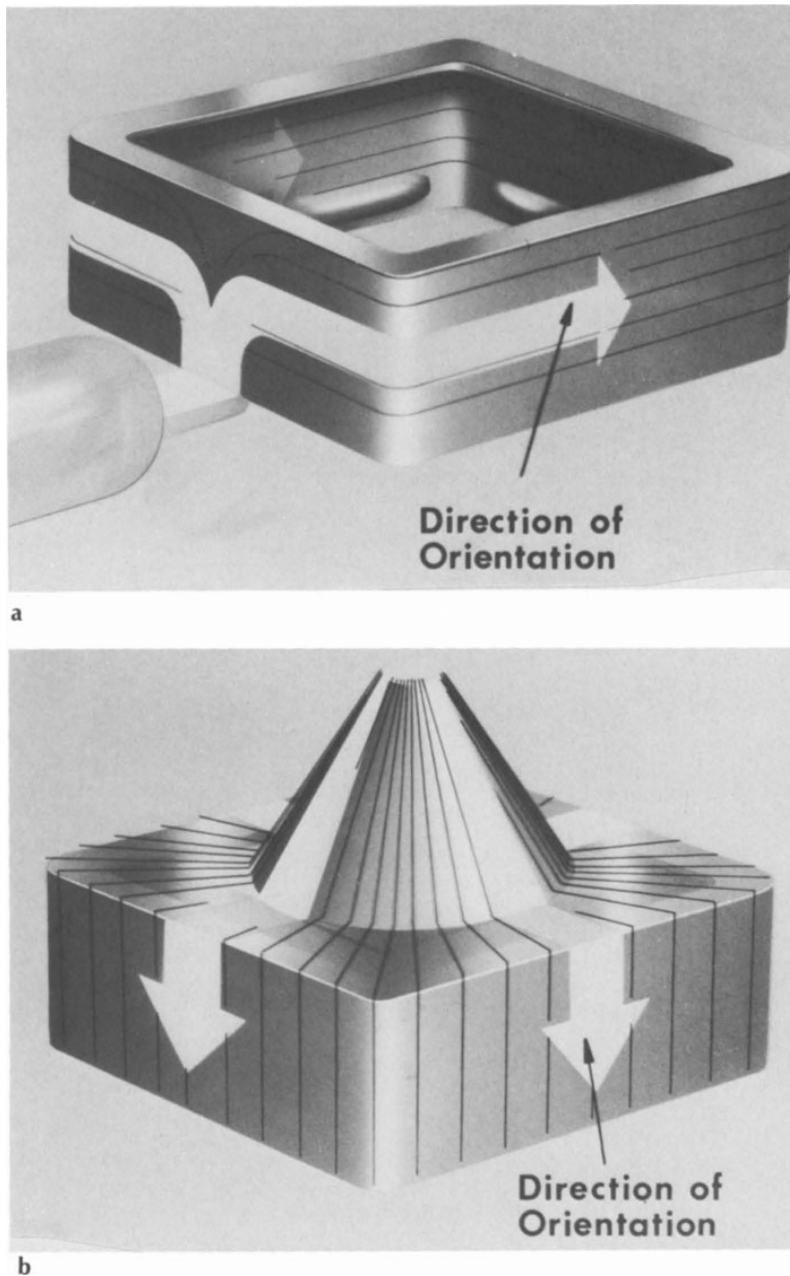


Figure 7-27. An example of locating a gate to obtain the required performance of a retainer product that is subject to being flexed in service. a) Retainer edge gated; b) retainer center gated; and c) left and center retainers (between fingers) that were edge gated, with the failed retainer on the right which was center gated.

620

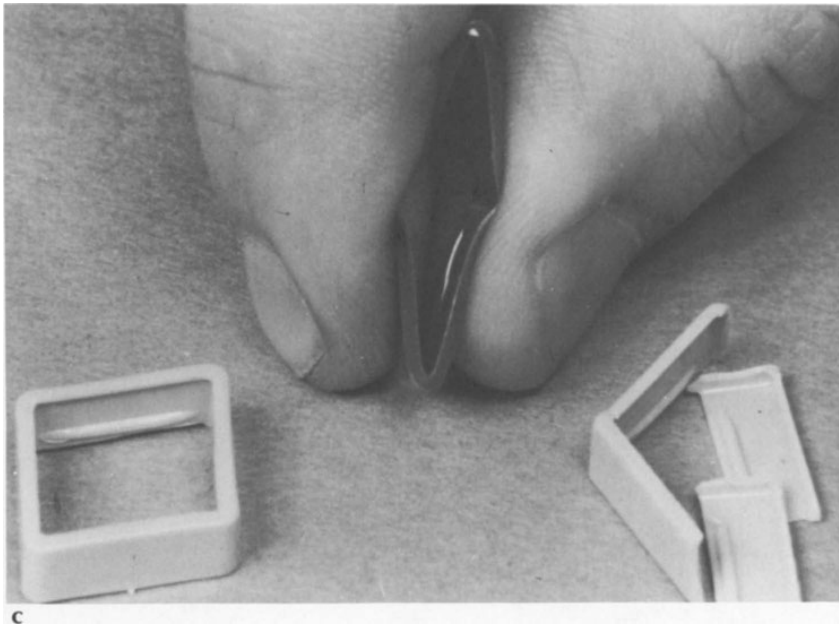


Figure 7-27. (Continued)

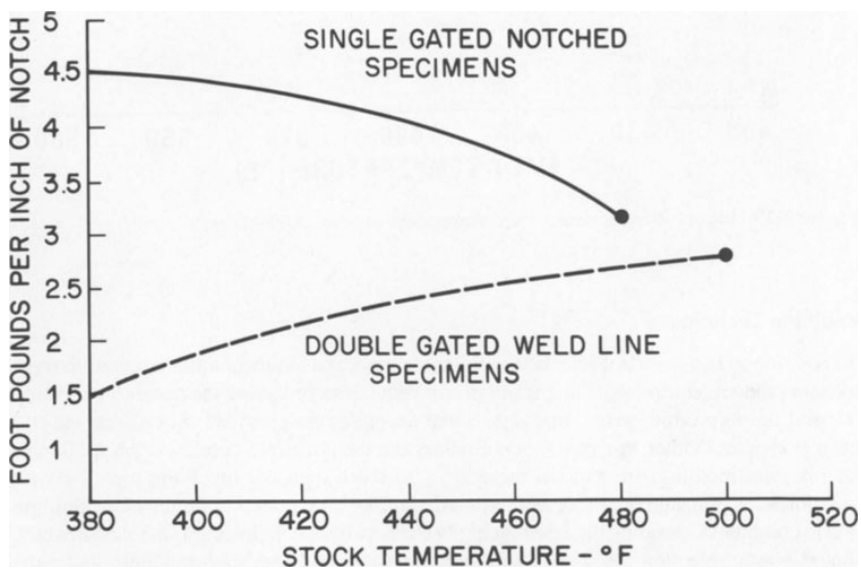


Figure 7-28. Izod impact strength of ABS plastic ($\frac{1}{8} \times \frac{1}{2} \times 3$ in. specimens).

621

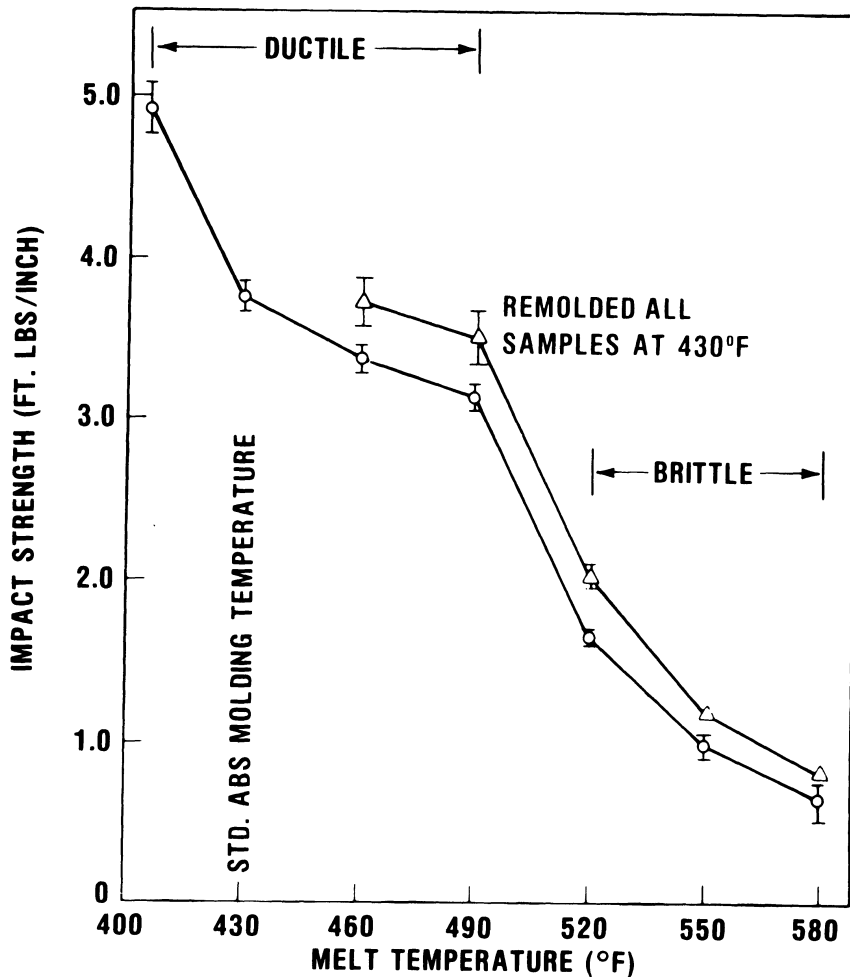


Figure 7-29. Impact strength versus melt temperature in white ABS plastic.

Molding Techniques

In addition to conventional injection molding, specialized IM techniques are used to meet certain product requirements that result in cost reductions or having the necessary molding capabilities to produce given products. Some examples are provided. See also at the end of this chapter "Other Processes," on coining and using fusible cores, including the use of injection molding. In addition there are also those methods involving molding with rotation stretching and orienting techniques that differ from injection stretch blow molding [12], continuous molding like producing Velcro strips [12], injection-molding metals, liquid plastic injection molding, foam molding, structural sandwich molding, and parts consolidation (see Fig. 7-30) and others [12].

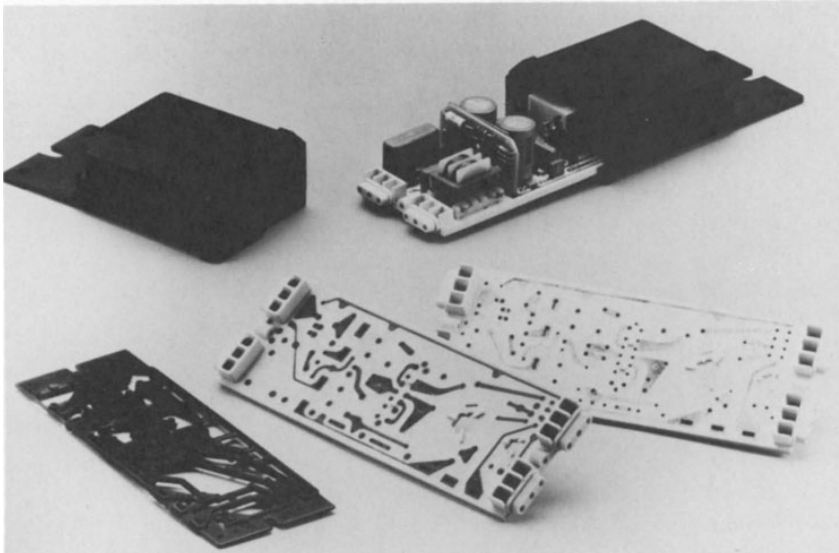


Figure 7-30. Du Pont's Arylon polyarylate and Rynite TP-polyester resins eliminate parts and simplify assembly of Xetec Corp.'s three-dimensional circuitboard for lighting ballasts. A special two-shot molding process removes the need for metal fabrication and yields a low-cost, reliable component for use in rapid-start fluorescent lighting ballasts.

Coinjection

Coinjection basically means that two or more different plastics are "laminated" together. These plastics could be the same except for color. When different plastics are used, they must be compatible in that they provide proper adhesion (if required), melt at approximately the same temperature, and so on (see Table 7-9). Two or more injection units are required, with each material having its own injection unit. The materials can be injected into specially designed molds—rotary, shuttle table, and the like [12].

The term *coinjection* can denote different products, such as sandwich construction, double-shot injection, multiple-shot injection, structural foam construction, two-color molding, and inmolding. Whatever its designation, a sandwich configuration has been made in which two or more plastics are "laminated" together to take advantage of the different properties each plastic contributes to the structure.

This form of injection has been in use since the early 1940s. Many different advantages exist. For example, 1) it combines the performance of materials; 2) it permits the use of a low-cost plastic such as a regrind; 3) it provides a decorative "thin" surface of an expensive plastic; 4) it includes reinforcements; 5) it permits the use of barrier plastics (see Chapter 4), and more. Coinjection molding is being redefined today in light of the approaches now available for molding such multicomponent parts as automotive taillights, containers, business machine housings, and so on.

624 DESIGNING WITH PLASTICS AND COMPOSITES: A HANDBOOK

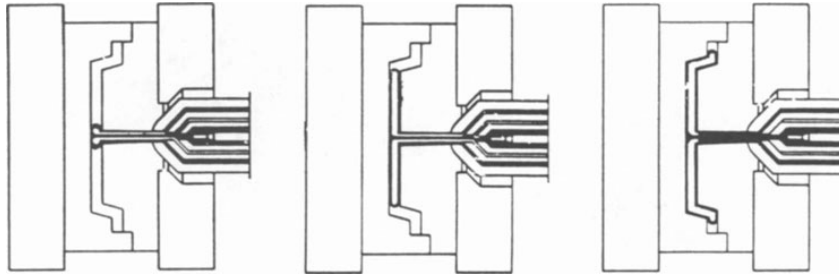


Figure 7-31. The three-channel coinjection system shown here simultaneously injects two different plastic melts. Courtesy of Battenfeld of America.

There are three techniques offered for multiple-component injection, called the one-channel, two-channel, and three-channel techniques (see Fig. 7-31 for the three-channel type) [12].

Gas Injection

Parts can be molded by gas injection using injection-molding machines. This process is most effective and economical when used for large parts. It offers a way to mold parts with only 10 to 50 percent of the clamp tonnage that would be necessary in conventional IM [12].

The technique—practiced in several variations, with some patented—involves the injection of an inert gas, usually nitrogen, into the melt as it enters the mold. This is not structural foam, as no foam core is produced; instead, the gas forms a series of interconnecting hollow channels in the thicker sections of the part. The gas pressure is maintained through the cooling cycle. In effect, the gas packs the plastic into the mold without a second-stage high-pressure packing in the cycle as used in IM, which requires high tonnage to mold large parts.

Molded-in stresses are minimal. The thick but hollow sections provide rigidity and do not create sink or warpage problems. The cycle time is reduced because the thick sections are hollow. As the gas is not mixed with the melt, there is no surface splay, which is typical of low-pressure structural foam molding [12]. Gas injection is now being used with commodity and engineering resins.

EXTRUSION

The extruder, which offers the advantages of a completely versatile processing technique, is unsurpassed in economic importance by any other process. This continuously operating process, with its relatively low cost of operation, is predominant in the manufacture of shapes such as films, sheets, tapes, filaments, pipes, rods, in-line postforming, and others. The basic processing concept is similar to that of injection molding (IM) in that material passes from a hopper into a cylinder in which it is melted and dragged forward by the movement of a screw. The screw compresses, melts, and homogenizes the material. When the melt reaches the end of the cylinder, it usually is forced through a screen pack prior to entering a die that gives the desired shape with no break in continuity (see Fig. 7-32) [10, 12, 601–25].

702 DESIGNING WITH PLASTICS AND COMPOSITES: A HANDBOOK

Various types of surface finishes are available for plastics and composite parts, such as smooth, textured, molded-in color, and in-mold coating. A textured part surface can be obtained through either a textured mold cavity or a postmold paint process. The former method is the most commonly used. A wide variety of texture designs is available. The surface smoothness, and to some degree the texture, of a plastic or composite is as dependent on the materials used in it as on the surface of the cavity. For example, certain textured surfaces can be obtained only if the proper steel or metal is used in the mold cavity. Also, with any mold the proper cavity steel based on the plastic processed will significantly reduce its wear and tear and extend its useful life [11, 12].

Cost

The production flexibility of the fabrication process is often the single most important economic factor in a plastic part. The component's size, shape, complexity, and required production rate can be primary determinants. As an example, small numbers of large objects tend economically to favor casting, as well as the RP's hand lay-up or spray-up process, with a minimal tooling cost and maximum freedom for design changes. Many products favor injection and compression molding or long runs in extruders, with their automation capabilities to minimize labor costs. Often the shape dictates the process, such as centrifugal casting or filament winding being used for cylindrical parts, rotational molding for complex hollow shapes or extremely large parts, and pultrusion for constant cross-sections requiring extremely high strength and stiffness. These general examples should be considered broadly, since individual processes can all be designed for a specific product capability to meet performance requirements at the lowest cost.

A further important point is that major costs can be incurred in the operations required after fabricating: trimming, finishing, joining, attaching hardware, and so on. Observing the following design practices will help reduce costs and improve processing and performance, whatever fabrication method is selected: 1) strive for the simplest shape and form; 2) use the shape of the product to provide stiffness, reducing its required number of stiffening ribs; 3) combine the parts into single moldings or extrusions as much as possible, to minimize assembly time and eliminate designing fasteners and so on; 4) use a uniform wall thickness wherever possible, and make changes in thickness gradually, to reduce stress concentrations; 5) use shape to satisfy functional needs like slots for hoisting, hand grips, and pouring; 6) provide the maximum radii that are consistent with the functional requirements; and 7) keep tolerances as liberal as possible, but once in production aim for tighter tolerances, to save plastic material and probably reduce production cost.

Minimizing cost is generally an overriding goal in any application, whether a process is being selected for a new product application or opportunities are being evaluated for replacing existing materials. The major elements of cost include capital equipment, tooling, labor, and inefficiencies such as scrap, repairs, waste, and machine downtime [12]. Each element must be evaluated before determining the most cost-effective process from among the available alternatives. To a great extent, the selection of a process for a new plastic or composite product will be dictated, or at least restricted by, the limitations imposed by design and cost factors. These factors frequently coincide to indicate the preferred processes. Some plastics will have a limited scope of processes available, but others will be more flexible. And parts for limited production or small volumes may require processes with low capital and tooling costs to make them economical.

Table 7-26. Specific Processing Methods as a Function of Part Design

Process	Ribs	Bones	Vertical Walls	Spherical Shape	Box Sections	Slides/ Cores	Weldable	Good Finish, Both Sides	Varying Cross- section
Thermoplastics									
Injection	Y	Y	Y	N	N	Y	Y	Y	Y
Injection compression	Y	Y	N	N	N	Y	Y	Y	Y
Hollow injection	Y	Y	Y	N	Y	Y	Y	Y	Y
Foam injection	Y	Y	Y	N	Y	Y	Y	Y	Y
Sandwich molding	Y	Y	Y	N	N	Y	Y	Y	Y
Compression	Y	Y	Y	N	N	Y	Y	Y	Y
Stamping	N	N	N	N	N	N	Y	Y	N
Extrusion	Y	N	N/A	N	Y	N	Y	Y	Y
Blow molding	N	N	Y	Y	Y	Y	Y	N	N
Twin-sheet forming	N	N	Y	Y	Y	N	Y	N	N
Twin-sheet stamping	N	N	N	N	Y	N	Y	Y	N
Thermoforming	N	N	Y	N	N	Y	Y	N	N
Filament winding	Y	N	Y	Y	Y	N	Y	N	Y
Rotational casting	N	N	Y	Y	N	N	Y	N	N
Thermosetting									
Compression									
Powder	Y	Y	Y	N	N	Y	N	Y	Y
Sheet molding compound	Y	Y	Y	N	N	Y	N	Y	Y
Cold-press molding	N	Y	Y	N	N	N	N	Y	Y
Hot-press molding	N	Y	Y	N	N	N	N	Y	Y
High-strength sheet molding compound	Y	Y	Y	N	N	N	N	Y	Y
Prepreg	N	N	Y	N	N	N	N	Y	Y
Vacuum bag	N	Y	Y	N	Y	N	N	N	Y
Hand lay-up	N	Y	Y	N	Y	N	N	N	Y
Injection									
Powder	Y	Y	Y	N	N	Y	N	Y	Y
Bulk molding compound	Y	Y	Y	N	N	Y	N	Y	Y
ZMC	Y	Y	Y	N	N	Y	N	Y	Y
Stamping	N	N	Y	N	N	N	N	Y	N
Reaction injection molding	Y	Y	N	N	Y	N	Y	Y	Y
Resin transfer molding, or resin inject	Y	N	Y	N	Y	N	N	Y	Y
High-speed resin transfer molding, or fast resin inject	Y	N	Y	N	Y	N	N	Y	Y
Foam polyurethane	Y	Y	Y	Y	Y	N	N	Y	Y
Reinforced foam	Y	Y	Y	N	Y	N	N	Y	Y
Filament winding	Y	N	Y	Y	Y	N	N	Y	Y
Pultrusion	Y	N	N/A	N	Y	N	N	Y	Y

Note: Y, yes; N, no; N/A, not applicable.

Table 7-27. Molding Process Guide to Plastic Materials*

Material Family	Injection	Compression	Transfer	Casting	Cold Molding	Coating	Structural Foam	Extrusion	Laminating	Sheet Forming	RP Molding FRP	Dip and Slush	Blow	Rotational
ABS	X						X	X		X			X	
Acetal	X						X	X		X			X	
Acrylic	X			X		X		X		X			X	
Allyl		X	X	X	X	X		X			X			
ASA	X						X	X		X				
Cellulosic	X						X	X		X			X	
Epoxy		X		X	X	X		X		X				
Fluoroplastic	X	X	X		X	X		X		X				
Melamine-formaldehyde	X	X	X	X	X	X		X						
Nylon	X			X	X	X	X	X					X	
Phenol-formaldehyde	X	X	X	X	X	X		X						
Poly (amide-imide)	X	X	X					X						
Polyarylether	X							X						
Polybutadiene	X		X					X					X	
Polycarbonate	X	X						X		X			X	
Polyester (TP)	X					X		X			X		X	
Polyester-fiberglass (TS)		X	X					X			X		X	
Polyethylene	X	X				X	X	X		X				
Polyimide	X	X				X		X(TP)						
Polyphenylene oxide	X						X	X						
Polyphenylene sulfide	X					X		X						
Polypropylene	X						X	X		X			X	
Polystyrene	X						X	X		X			X	
Polysulfone	X	X					X	X		X			X	
Polyurethane (TS) (TP)	X	X	X	X		X	X	X(TP)		X			X	
SAN	X						X	X		X				
Silicone		X		X				X						
Styrene butadiene	X					X		X						
Urea formaldehyde		X				X		X		X				
Vinyl	X	X				X	X	X		X		X	X	X

*Compounding permits using other processes.

Table 7-28. General Information Relating Processes and Materials to Properties of Plastics

Thermosets	Properties	Processes
Polyesters Properties shown also apply to some polyesters formulated for thermoplastic processing by injection molding	Simplest, most versatile, economical and most widely used family of resins, having good electrical properties, good chemical resistance, especially to acids	Compression molding Filament winding Hand lay-up Mat molding Pressure bag molding Continuous pultrusion Injection molding Spray-up Centrifugal casting Cold molding Comofom¹ Encapsulation
Epoxies	Excellent mechanical properties, dimensional stability, chemical resistance (especially alkalis), low water absorption, self-extinguishing (when halogenated), low shrinkage, good abrasion resistance, very good adhesion properties	Compression molding Filament winding Hand lay-up Continuous pultrusion Encapsulation Centrifugal casting
Phenolics	Good acid resistance, good electrical properties (except arc resistance), high heat resistance	Compression molding Continuous laminating
Silicones	Highest heat resistance, low water absorption, excellent dielectric properties, high arc resistance	Compression molding Injection molding Encapsulation
Melamines	Good heat resistance, high impact strength	Compression molding
Diallyl phthalate	Good electrical insulation, low water absorption	Compression molding
Thermoplastics		
Polystyrene	Low cost, moderate heat distortion, good dimensional stability, good stiffness, impact strength	Injection molding Continuous laminating
Nylon	High heat distortion, low water absorption, low elongation, good impact strength, good tensile and flexural strength	Injection molding Blow molding, Rotational molding
Polycarbonate	Self-extinguishing, high dielectric strength, high mechanical properties	Injection molding
Styrene-acrylo-nitrile	Good solvent resistance, good long-term strength, good appearance	Injection molding
Acrylics	Good gloss, weather resistance, optical clarity, and color; excellent electrical properties	Injection molding Vacuum forming Compression molding Continuous laminating
Vinyls	Excellent weatherability, superior electrical properties, excellent moisture and chemical resistance, self-extinguishing	Injection molding Continuous laminating Rotational molding
Acetals	Very high tensile strength and stiffness, exceptional dimensional stability, high chemical and abrasion resistance, no known room temperature solvent	Injection molding
Polyethylene	Good toughness, light weight, low cost, good flexibility, good chemical resistance; can be "welded"	Injection molding Rotational molding Blow molding

(cont'd)

Table 7-28. (Continued)

Thermosets	Properties	Processes
Fluorocarbons	Very high heat and chemical resistance, nonburning, lowest coefficient of friction, high dimensional stability	Injection molding Encapsulation Continuous pultrusion
Polyphenylene oxide modified	Very tough engineering plastic, superior dimensional stability, low moisture absorption, excellent chemical resistance	Injection molding
Polypropylene	Excellent resistance to stress or flex cracking, very light weight, hard, scratch-resistant surface, can be electroplated; good chemical and heat resistance; exceptional impact strength; good optical qualities	Injection molding Continuous laminating Rotational molding
Polysulfone	Good transparency, high mechanical properties, heat resistance, electrical properties at high temperatures; can be electroplated	Injection molding

¹Comoform is an extension of the cold molding process which utilizes a thermoformed plastic skin to impart excellent surface to a cold molded laminate.

Table 7-29. Economic Comparison of Three Different Processes

Production Considerations	Structural Foam	Injection Molding	Sheet Molding Compound
Typical minimum number of parts a vendor is likely to quote on for a single setup	250 (using multiple nozzle equip. with tools from other sources designed for the same polymer and ganged on the platen)	1,000 to 1,500	500
Relative tooling cost, single cavity	Lowest. Machined aluminum may be viable, depending on quantity required	20 percent more. Hardened-steel tooling	20 percent to 25 percent more. Compression-molding steel tools
Average cycle times for consistent part reproduction	2 to 3 minutes ($\frac{1}{4}$ in. nominal wall thickness)	40 to 50 seconds	1 $\frac{1}{2}$ to 3 minutes
Is a multiple-cavity tooling approach possible to reduce piece costs?	Yes	Yes. Depends on size and configuration, although rapid cycle time may eliminate the need.	Not necessarily. Secondary operations may be too costly and material flow too difficult
Are secondary operations required except to remove sprue?	No	No	Yes, e.g., removing material where a "window" is required (often done within the molding cycle)

(cont'd)

Table 7-29. (Continued)

Production Considerations	Structural Foam	Injection Molding	Sheet Molding Compound
Range of materials that can be molded	Similar to thermoplastic injection molding	Unlimited; cost depends on performance requirements	Limited; higher cost
Finishing costs for good cosmetic appearance	40 to 60 cents per sq. ft. of surface (depending on surface-swirl conditions)	None, if integrally colored; 10–20 cents per sq. ft. if painted	None, if secondary operations such as trimming are not required. Otherwise 20 to 30 cents per sq. ft. of surface

In summary, when considering alternative processes for producing plastic and composite products, the major concerns usually involve 1) limitations that may be imposed by the material, because not all materials can be processed by all methods; 2) limitations imposed by the design, such as the size, single-piece versus multiple-piece construction, a closed or open shape, and the level of dimensional and tolerance accuracy required; 3) the number of products required; and 4) the available capital equipment. Certain equipment may already be available and in use, although it may not necessarily be the one needed for the lowest production cost.

Table 7-30. Guide to Compatibility of Processes and Materials

	Thermosets						Thermoplastics									
	Polyester	Polyester SMC	Polyester BMC	Epoxy	Polyurethane	Acetal	Nylon 6	Nylon 6/6	Polycarbonate	Polypropylene	Polyphenylene sulfide	ABS	Polyphenylene oxide	Polystyrene	Polyester PBT	Polyester PET
Injection molding	•		•	•	•	•	•	•	•	•	•	•	•	•	•	
Hand lay-up	•			•												
Spray-up	•			•												
Compression molding	•	•	•	•							•					
Preform molding	•			•												
Filament winding	•			•												•
Pultrusion	•			•												
Resin transfer molding	•													•	•	•
Reinforced reaction injection molding	•			•	•		•									

Table 7-31. Design Recommendations for Choosing an RP Process

	Contact Molding, Spray-up	Pressure Bag	Filament Winding	Continuous Pultrusion	Premix/ Molding Compound	Matched Die Molding with Preform or Mat
Minimum inside radius, in.	1/4	1/2	1/8	N.A.*	1/32	1/8
Molded-in holes	Large	Large	N.R.*	N.A.	Yes	Yes
Trimmed-in mold	No	No	Yes	Yes	Yes	Yes
Built-in cores	Yes	Yes	Yes	N.A.	Yes	Yes
Undercuts	Yes	Yes	No	No	Yes	No
Minimum practical thickness, in. (mm)	0.060 (1.5)	0.060 (1.5)	0.010 (0.25)	0.037 (0.94)	0.060 (1.5)	0.030 (0.76)
Maximum practical thickness, in. (mm)	0.50 (13)	1 (25.4)	3 (76.2)	1 (25.4)	1 (25.4)	0.25 (6.4)
Normal thickness variation, in. (mm)	± 0.020 (± 0.51)	± 0.020 (± 0.51)	± 0.010 (± 0.25)	± 0.005 (± 0.1)	± 0.002 (± 0.05)	± 0.008 (± 0.2)
Maximum buildup of thickness	As desired	As desired	As desired	N.A.	As desired	2 to 1 maximum
Corrugated sections	Yes	Yes	Circumferential only	In longitudinal direction	Yes	Yes
Metal inserts	Yes	Yes	Yes	No	Yes	Yes
Surfacing mat	Yes	Yes	Yes	Yes	No	Yes
Limiting size factor	Mold size	Bag size	Lathe bed length and swing	Pull capacity	Press capacity	Press dimensions
Metal edge stiffeners	Yes	N.R.	Yes	No	Yes	Yes
Bosses	Yes	N.R.	No	No	Yes	Yes
Fins	Yes	Yes	No	N.R.	Yes	N.R.
Molded-in labels	Yes	Yes	Yes	Yes	No	Yes
Raised numbers	Yes	Yes	No	No	Yes	Yes
Gel coat surface	Yes	Yes	Yes	No	No	Yes
Shape limitations	None	Flexibility of the bag	Surface of revolution	Constant cross-section	Moldable	Moldable
Translucency	Yes	Yes	Yes	Yes	No	Yes
Finished surfaces	One	One	One	Two	Two	Two
Strength orientation	Random	Orientation of ply	Depends on wind	Directional	Random	Random
Typical glass percent by weight	30–45	45–60	50–75	30–60	25	30

*Note: N.A.: Not applicable.

N.R.: Not recommended.

Table 7-32. Comparison of Structural Foam with Five Other Processes

	Foam vs. Sheet Metal	Foam vs. Die Casting	Foam vs. Sheet Molding Compound	Foam vs. Hand Lay-up Fiberglass	Foam vs. Injection Molding
Advantages	1. Fabrication economy: less assembly time, tighter dimensional tolerances; increased product integrity; less final product-inspection time 2. Fewer parts required for assembly 3. Dent resistance 4. Elimination of oil canning 5. Greater design freedom 6. Better sound damping 7. Reduced damage from shipping 8. Reduced tooling costs for complex configurations	1. Much lower tooling costs 2. Longer tool life, lower maintenance 3. No trim dies required 4. Lighter weight 5. Higher impact resistance 6. Better sound damping 7. Better strength-to-weight 8. Better impact resistance	1. Uniform physical properties throughout the part 2. Warping and sink marks reduced or eliminated 3. No resin-rich areas to cause configuration problems 4. Higher impact resistance 5. Greater inherent structural capabilities 6. Lower shipping costs 7. Large parts more economical 8. Lower tooling costs 9. Better sound damping	1. More consistent part reproduction 2. Lower labor 3. Simplified assembly 4. Better dimensional stability 5. More design freedom 6. More uniform physical properties 7. Better sound damping	(Many process similarities exist) 1. Flexibility for functional engineering 2. Better low- to medium-volume economics 3. Lower tooling costs 4. Better large-part capability 5. Better sound damping 6. Lower internal stresses 7. Sink marks reduced or eliminated 8. Inherent structural strength
Limitations	1. Smaller variety of finishes available, such as chrome or baked enamel 2. No R.F.I. and grounding capabilities for cosmetic appearance 3. Harder to retrofit to frame or skins 4. Thicker wall 5. Higher tool costs than with brakeforming	1. No heat sink capabilities 2. No R.F.I. and grounding capabilities 3. Fewer available finishes for cosmetic appearance 4. Higher finishing costs 5. Thicker walls 6. Possible internal voids	1. Increased finishing costs (surface swirl) 2. Heat distortion 3. Thicker wall 4. Lower physical properties 5. Possible internal voids	1. More prone to heat distortion 2. Poorer economies of part size vs. quantity 3. Thicker walls 4. Higher tooling costs	1. Poorer surface finish 2. Application of cosmetic detail for appearance parts 3. Longer cycle time 4. Thicker walls 5. Poorer high-volume economics 6. Less equipment available for various shot sizes
Potential Savings from Structural Foam (in %)	50 + *	15 to 30	Up to 30	50 +	15 to 20†

*Even with limited quantities.
†Depending on unit volume and part size.

Chapter 11

DESIGN FEATURES THAT INFLUENCE PERFORMANCE

BASIC DETRACTORS AND CONSTRAINTS

In Chapters 3 through 5, 7, and 8 in particular some of the design problems of plastics were discussed. This chapter provides more detail on this important subject. Even though some of the analyses here will pertain to a specific process, many will relate to other processes, so it is best to review them all. Also, most of the characteristics of plastics that detract from their effectiveness refer to injection molding and provide guidelines for all the processes. Although it is not actually the product designer's job to do so, the designer should have some idea of where problems can develop, based on how a mold or die is designed and manufactured [1, 2, 5–14, 21–32, 40–42, 45–46, 50, 55–68, 166, 208, 225, 253, 409, 478, 498, 564–70, 593, 637, 674, 807–15].

The successful design and fabrication of good plastic products requires a combination of sound judgment and experience. Designing good products requires a knowledge of plastics that includes their advantages and disadvantages and some familiarity with processing methods. Until the designer becomes familiar with processing, a fabricator must be taken into the designer's confidence early in development and consulted frequently during those early days. The fabricator and mold or die designer should advise the product designer on materials behavior and how to simplify processing. The designer should not become restricted by understanding only one process, particularly just a certain narrow aspect of it (see Chapter 7) [10–14, 32, 33, 40–42].

One of the earliest steps in product design is to establish the configuration of the parts that will form the basis on which strength calculations will be made and a suitable material selected to meet the anticipated requirements. During the sketching and drawing phase of working with shapes and cross-sections there are certain design features with plastics that have to be kept in mind to avoid degradation of the properties. Such features may be called property detractors or constraints. Most of them are responsible for the unwanted internal stresses that can reduce the available stress level for load-bearing purposes. Other features, which are covered in this chapter, may be classified as precautionary measures that may influence the favorable performance of a part if they are properly incorporated [4–6].

Although there is no limit theoretically to the shapes that can be created, practical considerations must be met. These relate not only to part design but also to mold or die design, since these must be considered one entity in the total creation of a usable,

789

790 DESIGNING WITH PLASTICS AND COMPOSITES: A HANDBOOK

economically feasible part. In the sections that follow, various phases considered important in the creation of such parts are examined for their contribution to and effect on design and function.

Prior to designing a part, the designer should understand such basic factors as those summarized in Table 11-1 and Figure 11-1. Success with plastics, or any other material, for that matter, is directly related to observing design details. For example, something as simple as a stiffening rib is different for an injection molded or structural foam part, even though both parts may be molded from the same plastic (see Fig. 11-1). However, a stiffening rib that is to be molded in a low-mold-shrink, amorphous TP will differ from a high-mold-shrinkage, crystalline TP rib, even though both plastics are just injection molded (see Chapter 2). Ribs molded in RP/composite plastics have their own distinct requirements (see Chapter 5). Hollow stiffening ribs of the type produced by thermoforming, blow, or rotational molding have the same function, but they are designed to be totally different [807].

The important factors to consider in designing can be categorized as follows: part thickness, tolerances, ribs, bosses and studs, radii and fillets, draft or taper, holes, threads, color, surface finish and gloss level, decorating operations, the parting line, gate locations, molded or extruded part shrinkage, assembly techniques, mold or die design, production volume, the tooling and other equipment amortization period, as well as the plastic and process selected. The order that these factors follow can vary, depending on the product to be designed and the designer's familiarity with particular materials and processes.

Preparing a complete list of design constraints is a crucial first step in plastic part design; failure to take this step can lead to costly errors. For example, a designer might have an expensive injection mold prepared, designed for a specific material's shrink value, only to discover belatedly that the initial material chosen did not meet some overlooked design constraint. Flammability, glass-fiber fillers to provide a higher modulus, and other requirements are best considered before a tool is made. Otherwise, the designer may have the difficult if not impossible task of finding a plastic that does meet all the design constraints, including the important appropriate shrink value for the existing mold. Such desperation in the last stages of a design project can and should be avoided. As emphasized from one end of this book to the other, it is vital to set up complete checklist of product requirements, to preclude the possibility that a critical requirement may be overlooked initially. Recognize that the "impossible" as well as the "approaches"

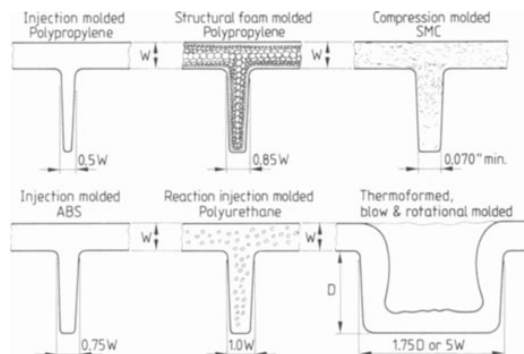


Figure 11-1. An example of how different plastics and molding processes can affect the design details of a stiffening rib.

to be avoided can in most cases still produce excellent products; however it is easier to take the direction with the least number of problems.

Tolerances and Shrinkages

Two different forms of shrinkage must be considered when designing to meet tolerances: the initial shrinkage that occurs while a part is cooling, called the mold or die shrinkage, and that which occurs after as many as twenty-four hours, called the after-shrinkage or after-swell. Some plastics are more stable than others after aging, regardless of their initial shrinkage. In many cases low shrinkage may indicate greater stability. As noted earlier, some plastics have zero shrinkage, with others having little or a high degree of shrinkage; see Chapters 3 to 7.

Large, unpredictable shrinkages can make close-tolerance designing almost impossible, so these must be indicated on the drawings. If it has been determined in advance that a part must be postcured, stress relieved, or baked, allowance must be made for probable additional shrinkage. These requirements must be specified on the drawings.

Especially for long runs, mold or die design is an important factor. The metals that will be used, particularly in mold cavities, and the forces required will largely be determined by the complexity of the product design. This complexity will, of course, dictate in turn the intricacy of the tool design that will eventually be used. In general, pack hardening, oil hardening, and prehardened steels are used, with materials such as beryllium copper and electroformed cavities finding use in applications for specialized purposes [10–12]. Chrome plating is frequently used to protect parts from the corrosive effect of volatiles present in some materials. Plating not only produces high luster and prevents tool staining but also eliminates the sticking of parts on removal from a mold or die. However, plating will only duplicate an existing surface, so the tool itself must be highly polished before being plated. The intricacy required in tool design, and the commensurate costs, may be leading factors when choosing a plastic.

If the material must flow around pins, spiders, and projections, it must have suitable flow properties and weld properly, leaving only minimal flow marks (see Chapter 7). Thus, the availability of the proper material becomes an important consideration.

Residual Stresses

Such processing-induced residual stresses that influence properties as mechanical, physical, environmental, and aesthetic factors (which also exist in other materials like metals and ceramics) can have favorable or unfavorable effects, depending on the application of the load with respect to the direction of the stresses or orientation. For example, at room temperature an unoriented PS is a brittle, glassy, amorphous polymer, whereas a uniaxial oriented PS is highly anisotropic. High tensile strength, elongation, and resistance to environmental stress crazing and cracking are achieved in the direction of orientation. However, an oriented PS is weaker and more susceptible to stress crazing in its transverse direction than is an unoriented PS. A biaxially oriented PS is strong and tough in all directions [12, 19, 42, 201, 225].

Residual stresses and molecular orientation play an important role in the toughness enhancement of cold-worked plastics, because toughness is primarily based on the mechanics of craze formation and shear band (crazes and flaws) formation. The shear bands determine the fracture mode and toughness of a polymer when subjected to impact loads. The amount of energy dissipated will depend on whether the material surrounding the

Table 11-1. Design Guides for Processes versus Product Requirements*

		Compression Molding			Injection Molding (Thermoplastics)	Cold Press Molding	Spray-up and Hand Lay-up
		Sheet Molding Compound	Bulk Molding Compound	Preform Molding			
Minimum inside radius, in. (mm)		1/16" (1.59)	1/16" (1.59)	1/8" (3.18)	1/16" (1.59)	1/4" (6.35)	1/4" (6.35)
Molded-in holes		Yes	Yes	Yes	Yes	No	Large
Trimmed in mold		Yes	Yes	Yes	No	Yes	No
Core pull & slides		Yes	Yes	No	Yes	No	No
Undercuts		Yes	Yes	No	Yes	No	Yes
Minimum recommended draft, in./°		1/4" to 6" (6.35–152 mm) depth: 1° to 3° 6" (152 mm) depth and over: 3° or as required					0°
Minimum practical thickness, in. (mm)		.050" (1.3)	.060" (1.5)	.030" (0.76)	0.35" (0.89)	.080" (2.0)	.060" (1.5)
Maximum practical thickness, in. (mm)		1" (25.4)	1" (25.4)	.250" (6.35)	.500" (12.7)	.500" (12.7)	No limit

Normal thickness variation, in. (mm)		$\pm .005$ (± 0.1)	$\pm .005$ (± 0.1)	$\pm .008$ (± 0.2)	$\pm .005$ (± 0.1)	$\pm .010^*$ (± 0.25)	$\pm .020^*$ (± 0.51)
Maximum thickness buildup, heavy buildup and increased cycle		As req'd.	As req'd.	2-to-1 max.	As req'd.	2-to-1 max.	As req'd.
Corrugated sections		Yes	Yes	Yes	Yes	Yes	Yes
Metal inserts		Yes	Yes	Not recommended	Yes	No	Yes
Bosses		Yes	Yes	Yes	Yes	Not recommended	Yes
Ribs		As req'd.	Yes	Not recommended	Yes	Not recommended	Yes
Molded-in labels		Yes	Yes	Yes	No	Yes	Yes
Raised numbers		Yes	Yes	Yes	Yes	Yes	Yes
Finished surfaces (reproduces mold surface)		Two	Two	Two	Two	Two	One

*Parallel or perpendicular to ram action and with slides in a tooling or split mold. Courtesy Owens Corning Fiberglas Corp.

flaws deforms plastically. For toughness enhancement the residual stresses play an important role in the suppression of craze formation, by avoiding the stress state that promotes brittle fracture.

The term *residual stresses* identifies the system of stresses that are in effect locked into a part, even without external forces acting on it. For instance, minute stresses may be induced in a material by nonuniform heating and cooling. The production of residual stresses is usually the result of nonhomogeneous plastic deformation occurring during thermal and mechanical actions, arising from changes in either volume or shape. Thermal treatments like quenching (rapid cooling) and annealing (slow cooling) introduce changes in physical and mechanical properties. For example, with sheet plastic the stresses created by quenching are the result of uneven cooling, when the surfaces cool faster than the core. This produces nonuniform volume changes and properties throughout the thickness. The compressive stresses on the surfaces of the quenched plastic produce tensile stresses in the core, which maintain the equilibrium of the forces.

Cold Working

Generally, a variety of mechanical deformation processes cause the nonuniform deformation that results in the formation of residual stresses. This nonhomogeneous deformation in a material is produced by the material's parameters—largely its process parameters, such as the tool geometry and frictional characteristics. For example, the rolling of a strip can be accomplished by using squeeze rolls. In the rolling process, parameters with a small roll diameter and little reduction produce deformation penetration that is shallow and close to the surface, whereas the interior of the strip remains almost undeformed. After the removal of the deformation forces and a complete elastic recovery, this condition produces compressive residual stresses at the surface and tensile residual stresses in the core.

The logic of this situation is that the surface material is forced to elongate more than the relatively rigid core permits. When there is a large diameter and much reduction, the deformation penetration occurs deeper in the core and there is a tendency for the plastic to lag at the surface, the result of friction at the material-to-tool interface. Thus, the cold working processes like rolling, drawing, extrusion, and forging produce residual stresses along with their molecular orientation [509].

Generally, the more discussed and technically reviewed residual stresses are in injection-molded parts. Their presence can often be detected qualitatively by immersing TP parts in appropriate stress-cracking solutions for a short time, then observing the crazing caused by surface tensile residual stresses (see Chapter 4). Such methods are ineffective for a part with compressive or insufficient tensile stresses on its surface. To determine their magnitude includes the layer removal technique of microtoming (see Chapter 9).

Stress Concentrations

Sharp corners should always be avoided in designing, particularly when working with TP injection-molded parts. Although sharp-cornered designs are common with certain sheet metal and machined parts, good design practice in any material dictates the use of generous radii, to reduce stress concentrations. Reinforced plastics and composites and metal parts will often tolerate sharp corners, because the stresses at their corners are low compared to the strength of the material or because localized yielding redistributes the load. However, neither of these factors should be relied upon in TP molded parts. Sharp

corners, particularly the inside corners, can cause severe molded-in stresses as a material shrinks onto the corner, as well as poor flow patterns, reduced mechanical properties, and increased tool wear.

The elementary formulas used in design are based on structural members having a more or less constant cross-section, or at least only a gradual change of contour, but these conditions are seldom found in practice. The presence of shoulders, bosses, grooves, holes, threads, and corners results in modifying the simple stress distribution and in localized, higher stresses. This localization, known as the stress concentration factor, is defined as $K = \text{maximum stress divided by nominal stress}$. Localized high stresses must in most cases be determined experimentally rather than theoretically. The photoelastic technique is one of the more effective methods used to do this. To interpret a photoelastic diagram qualitatively it is sufficient to know that the number of fringes (the density of lines) is proportional to the absolute stress level.

Basically, in the vicinity of a sharp corner all fringes converge toward the apex. Having a high density of lines at this point indicates the presence of high stress level. At a rounded corner there will be considerably less concentration. Besides the molding problems, sharp corners often cause premature failure because of the stress concentration. To avoid these problems, inside corner radii should be equal to one-half the nominal wall thickness, with a 0.020 in. radius considered as a minimum for parts subjected to stress and a 0.005 in. minimum for the stress-free regions of a part. Having inside radii less than 0.005 in. is not recommended for most materials. Outside corners should have a radius equal to the inside corner plus the wall's thickness.

Figure 11-2 illustrates quantitatively the effect of fillet radius (r) on stress concentration factor (K). Assume that a force or load is being exerted on the cantilevered section shown. As the radius is increased, with all other dimensions remaining constant, r/t increases

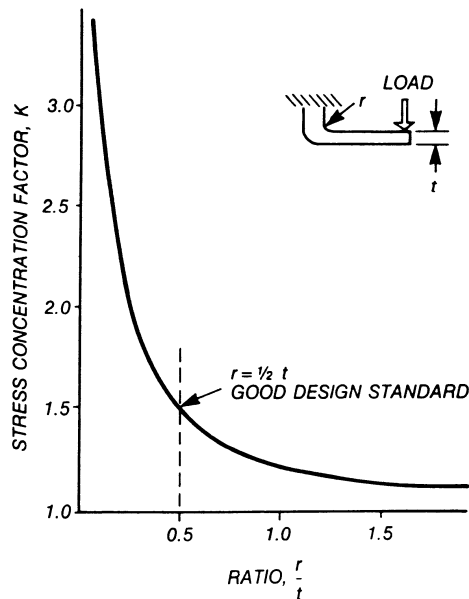


Figure 11-2. The effect of the fillet radius on the stress-concentration factor. To find the stress from having a small radius, multiply the calculated bending stress by K .

796 DESIGNING WITH PLASTICS AND COMPOSITES: A HANDBOOK

proportionally and the stress-concentration factor decreases, as shown by the curve. The K factor can be reduced by 50 percent, from 3.0 to 1.5, by increasing the r/t sixfold, from 0.1 to 0.5. This curve shows how readily the K factor can be reduced by using a large fillet radius. A fillet with an optimal design is obtained with an r/t of 0.5. A further increase in the radius reduces the stress concentration by a marginal amount. Stress concentration factors on the same order of magnitude have also been determined for grooves, notches, holes, screw threads, bosses, and ribs [810].

INJECTION MOLDING

Design Concepts

In designing a totally new product or redesigning an existing one to improve the product, bring about cost savings, or some combination of these or other reasons, consideration should be given to the key advantages of injection molding (IM). These advantages include the ability to produce finished, multifunctional, or complex molded parts accurately and repeatedly in a single, highly automated operation (see Chapter 7). While keeping this in mind during the initial planning stage, one should also be aware of the general design considerations presented in this section [1, 2, 5–12, 40–46, 50–70, 86, 231, 409, 564, 569, 593, 807].

Many parts of an injection mold will influence the final product's performance, dimensions, and other characteristics. These mold parts include the cavity shape, gating, parting line, vents, undercuts, ribs, hinges, and so on (see Table 11-2). The mold designer must take all these factors into account. At times, to provide the best design the product designer, processor, and mold designer may want to jointly review where compromises can be made to simplify meeting product requirements. With all this interaction, it should be clear why it takes a certain amount of time to ready a mold for production.

Thus, in the design of any IM part there are certain desirable goals that the designer should use. In meeting them, problems can unfortunately develop. For example, the most

Table 11-2. Functions of an Injection Mold

Mold Component	Function Performed
Mold base	Hold cavity (cavities) in fixed, correct position relative to machine nozzle
Guide pins	Maintain proper alignment of the two halves of a mold
Sprue bushing (sprue)	Provide means of entry into mold interior
Runners	Convey molten plastic from sprue to cavities
Gates	Control flow into cavities
Cavity (female) and force (male)	Control size, shape, and surface texture of molded article
Water channels	Control temperature of mold surfaces, to chill plastic to rigid state
Side (actuated by cams, gears, or hydraulic cylinders)	Form side holes, slots, undercuts, threaded sections
Vents	Allow escape of trapped air and gas
Ejector mechanism (pins, blades, stripper plate)	Eject rigid molded article from cavity or force
Ejector return pins	Return ejector pins to retraced position as mold closes for next cycle

DESIGN FEATURES THAT INFLUENCE PERFORMANCE 797

common mold design errors of a sort that can be eliminated usually occur in the following areas:

- Thick/thin sections, transitions, warp, and stress
- Multiple gates and weld lines
- Wrong gate locations
- Inadequate provision for cavity air venting
- Parts too thin to mold properly, as diaphragms
- Parts too thick to mold properly
- Plastic flow path too long and tortuous
- Runners too small
- Gates too small
- Poor temperature control
- Runner too long
- Part symmetry vs. gate symmetry
- Orientation of polymer melt in flow direction
- Hiding gate stubs
- Stress relief for interference fits
- Living hinges
- Slender handles and bails
- Thread inserts
- Creep or fatigue over long-time stress (extremely important)

As seen in previous chapters, different plastics have different melt and flow characteristics. What is used in a mold design for a specific material may thus require a completely different type of mold for another material. These two materials might, for instance, have the same polymer but use different proportions of additives and reinforcements. This situation is no different than that of other materials like steel, wood, ceramics, and aluminum.

It is important to recognize that the drawing of a plastic product will not specifically spell out the way many of its details will be carried out in the mold design. Some features adversely affect the strength and quality of the molded product. In most cases, these problem details can be modified by the designer to minimize their adverse effects on the properties of the part [12, 46].

What follows is a general summary of how to reduce problems to tolerable limits.

First, inside sharp corners should normally be shown as two intersecting straight lines, without specific indication as to the functional requirement or degree of sharpness. Inside square corners are stress-concentration areas, quite similar to a notch in a test bar. The Izod impact strength of notched and unnotched test bars shows the relative impact strength of each material at the two conditions.

Thus, for example, polycarbonate has an impact strength of the notched $\frac{1}{8}$ -in. test bar of 12 to 16 ft.-lb./in. of notch, whereas the same bar unnotched does not fail the test. Polypropylene has an impact strength 30 times greater in the unnotched than the notched bar. Nylon shows a drastic increase in impact strength as the radius increases from sharpness to $\frac{3}{4}R$. A similar trend exists for most other materials. These examples point out that brittleness increases with the decreasing of a radius in a corner. Visually, a radius of 0.020 in. on a plastic part may be considered sharp, with an influence on strength that is much more favorable than a radius of 0.004 in. To the moldmaker, a sharp corner is

798 DESIGNING WITH PLASTICS AND COMPOSITES: A HANDBOOK

usually easier to produce, but in the plastic part it is a source of brittleness and, in most cases, is highly undesirable. Inside sharp corners on plastic-part drawings are a frequent occurrence. It is the mold designer's responsibility to call attention to such strength degradation and invite appropriate corrective measures.

Second, varying wall thicknesses from thick and thin sections in a part will lead to problems in molding. Having a uniform wall throughout a part gives it good strength and appearance. Thick and thin sections will have molded-in stresses, different rates of shrinkage (causing warpage), and possibly void formation in the thick portion. Since the parts in a mold solidify from their outer surfaces toward the center, sinks will tend to form on the surface of a thick portion. When thick ($\frac{3}{16}$ in. and over) and thin ($\frac{1}{8}$ in. or less) portions are unavoidable, the transition should be gradual and coring should be utilized whenever possible.

Third, sinks are not only the result of the causes listed above but also occur whenever supporting or reinforcing ribs, flanges, or similar features are used in an attempt to provide functional service without changing the basic wall thickness of a product. If the appearance of a sink on the surface is objectionable, the ribs and transition radius should be proportioned so that their contribution to the sink is minimal. Figure 11-3 is a guide to the dimensioning of ribs.

Fourth, molded-in metal parts should be avoided whenever alternate methods will accomplish the desired objectives. If it is essential to incorporate such inserts, they should be shaped so that they will present no sharp inside corners to the plastic. The effect of the sharp edges of a metal insert would be the same as explained in the first point above, namely, brittleness and stress concentration. The cross-section that surrounds a metal insert should be heavy enough that it will not crack upon cooling. A method of minimizing cracking around the insert is to heat the metal insert prior to mold insertion to a temperature of 250 to 300°F so that it will tend to thermoform the plastic into its finished shape. The thickness of the plastic enclosure will vary from material to material. A reasonable guide is to have the thickness 1.75 to 2 times the size of the insert diameter.

Fifth, most plastic parts are used in conjunction with other materials. If the use temperature is other than room temperature, certain compensatory steps must be taken to avoid problems arising from the difference in the thermal coefficients of expansion of the different materials. Many plastic materials expand about ten times as much as steel. Thus, careful analysis of the conditions under which the metallic materials are coemployed for functional uses is called for. In the automotive industry many long plastic parts are used in conjunction with metal frames. If proper compensation is not made for the

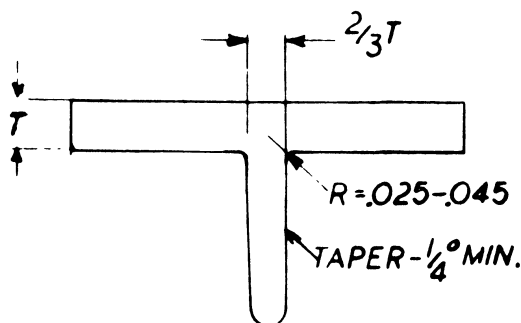


Figure 11-3. Rib and wall dimensioning.

difference in thermal coefficients of the materials, buckling or looseness may result, causing noise or a poor appearance.

Finally, plastic threads have a very limited strength and may be further degraded if the thread form is not properly shaped. The V-shaped portion at the outside of a female thread will present a sharp inside corner that will act as a stress concentrator and thereby weaken the threaded cross-section. A rounded form that can be readily incorporated in a molding insert will appreciably improve the strength over a V-shaped form. When self-tapping, thread-cutting, or thread-form screws are used, their holding power can be increased if either the screws or plastic parts are heated to a temperature of 180 to 200°F at joining time. This will provide thermoforming action to some degree and keep the stress level caused by the joining action at a low point.

These possible sources of problems in a molded part should be marked on the part drawing and explained to the product designer for corrective action or creating an awareness of possible product defects from design limitations. This is a necessary step in the chain of events in which the aim is to produce a tool that will provide parts for a good working product. Even if the mold's design, workmanship, and operation are carried out to the highest degree of quality, they cannot overcome a built-in weakness of product design.

Sharp Corners

When a part drawing does not show a radius, the tendency is for the toolmaker (while making a mold) to leave the intersecting machined or ground surfaces as they are generated by the machine tool. The result is a sharp corner on the molded part. Such sharp corners on the insides of parts are the most frequent property detractors.

The material data sheet should show the difference in impact strength between notched and unnotched test bars. In some materials this ratio is 1 to 30, but in others there is also a decided reduction in the strength of the notched bars. Some show no strength reduction, however. In a shaped product an inside sharp corner is an indication that a certain specified tough material acts in a brittle manner. Sharp corners become stress concentrators.

The stress-concentration factor increases as the ratio of the radius R to the part thickness T decreases. An R/T of 0.6 is favorable, and an increase in this value will be of some limited benefit. If certain other details in this problem are properly counteracted, that will help in reducing stress concentration. In Figure 11-4, we can see that a concentric radius, in addition to eliminating the outside sharp corner, can play an important part in holding down the value of the stress concentration.

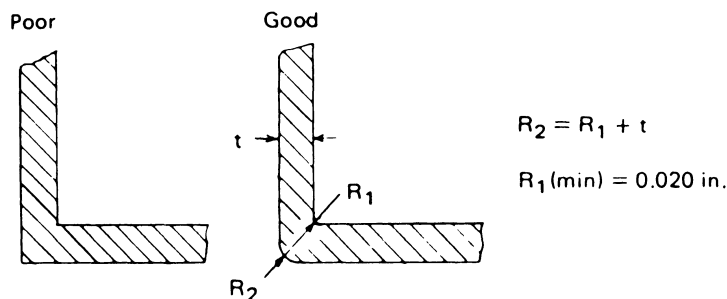


Figure 11-4. An inside corner.

800 DESIGNING WITH PLASTICS AND COMPOSITES: A HANDBOOK

The ASTM Izod impact strength of nylon with various notch radii is shown in Figure 11-5. Thus, we see that with a radius of 0.005 in. the impact strength is about 1.3 ft.-lb./in., with an R of 0.020 in. it is 4.5 ft.-lb./in., and with an R of 0.040 in. it is 12 ft.-lb./in. In most cases a radius of 0.020 in. can be considered a sharp corner as far as end use is concerned, a size that is a decided improvement over a 0 to 5 mil radius; therefore, it should be considered a minimum requirement and be so specified. If this radius of 0.020 in. causes interference, a corner such as shown in Figure 11-6 should be considered.

The recommended radius not only reduces the brittleness effect but also provides a streamlined flow path for the plastic in the mold. The radiused corner of the metal in the mold reduces the possibility of its breakdown and thus eliminates a potential repair need. Too large a radius is also undesirable because it wastes material, may cause sink marks, and may even contribute to stresses, from having excessive variations in thickness.

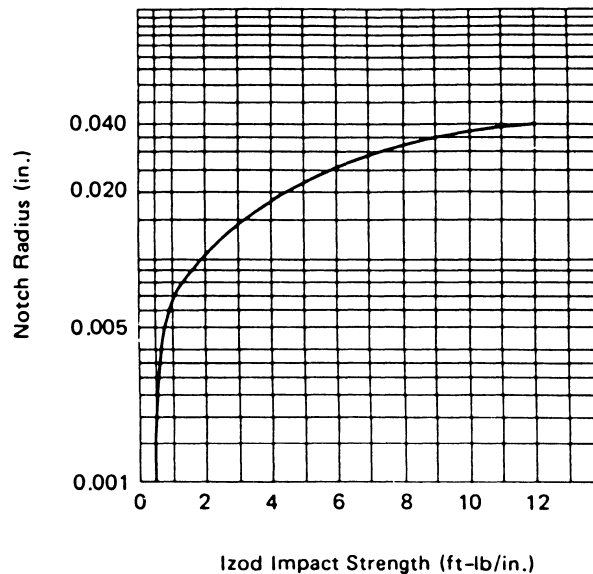


Figure 11-5. A radius of notched Izod impact strength for nylon.

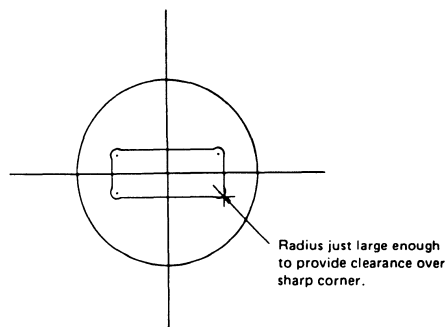


Figure 11-6. A clearance radius for a sharp corner.

DESIGN FEATURES THAT INFLUENCE PERFORMANCE 801

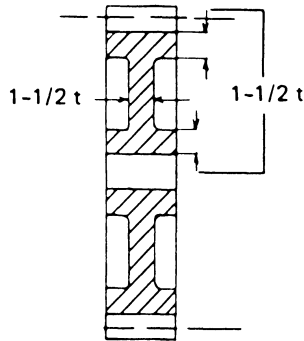


Figure 11-7. A solid-steel gear.

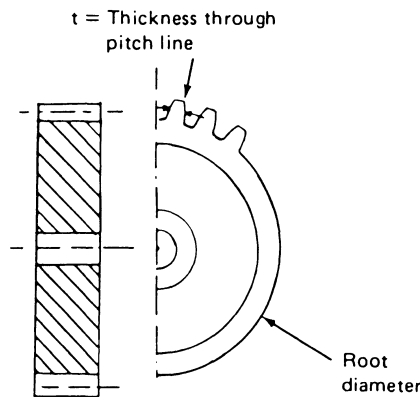


Figure 11-8. A plastic design of the steel gear shown in Figure 11-7.

Uniform Wall Thickness

Wall requirements are usually governed by the load, the support needs for other components, attachment bosses, and other protruding sections.

Designing a part to meet all these requirements while still producing a reasonably uniform wall will greatly benefit its durability. A uniform wall thickness will minimize stresses, differences in shrinkage, possible void formation, and sinks on the surface; it also usually contributes to material saving and economy in production.

Most of the features for which heavy sections are intended can be modified by means of ribbing, coring, and shaping of the cross-section to provide equivalent strength, rigidity, and performance. Figure 11-7 shows a small gear manufactured from metal bar stock. The same gear converted to a molded plastic would be designed as shown in Figure 11-8. This plastic gear design, compared to copying the metal gear, saves material, eliminates stresses from having thick and thin sections, provides uniform shrinkage in teeth and the remainder of the gear, avoids the danger of warpage, with its thin web and tooth base prevents bubble formation and potential weak spots, and, having no sink in the middle of the thickness, provides a full load-carrying capacity for the teeth.

802 DESIGNING WITH PLASTICS AND COMPOSITES: A HANDBOOK

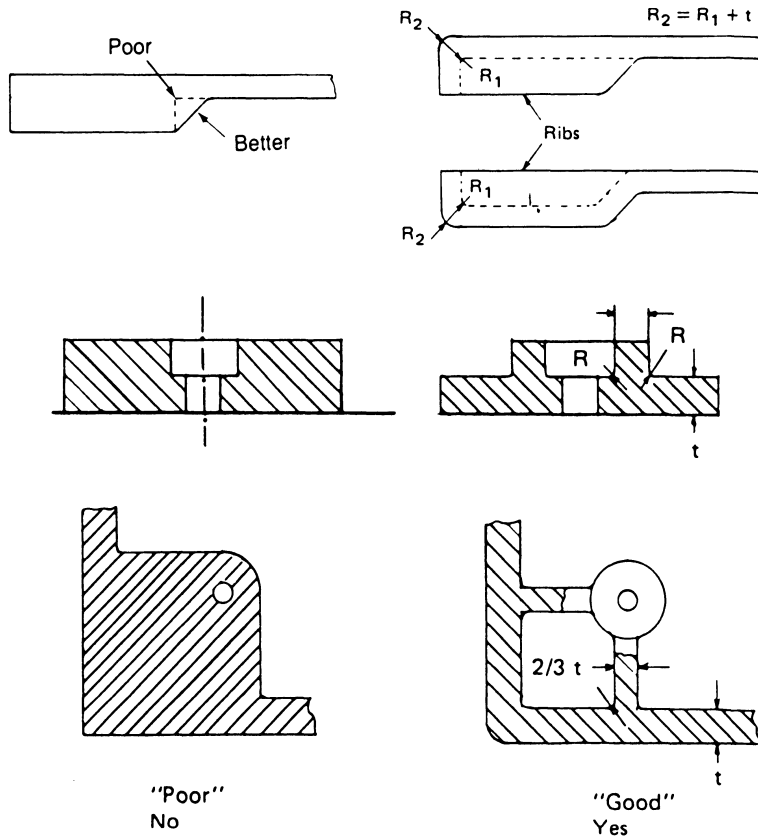


Figure 11-9. Poor and better design features.

Figure 11-9 illustrates both well and poorly designed cross-sections. If a case exists where some thickness variation is unavoidable, the transition should be gradual, to prevent sharp changes in temperature during solidification.

Wall Thickness Tolerance

When relatively deep parts are being designed, a tolerance for the wall thickness on the order of ± 0.005 in. is usually given. What this tolerance should mean is that a product will be acceptable when made with this tolerance, but that the wall thickness must be uniform throughout the circumference.

If we analyze the molding condition of such a part and assume that one side is made to minimum specifications and the opposite to maximum specifications, we find the following taking place: the resistance to plastic flow decreases with the third power of the thickness, which means that the thick side will be filled first, while the thin side will fill from all sides, instead of the gate side alone. This type of filling creates a pocket on the thin side and compresses the air and gases to such a point that the rising temperature caused by compression causes the material to be charred while the pocket is filling up.

DESIGN FEATURES THAT INFLUENCE PERFORMANCE 803

The charred material will create porosity, a weak area, and an electrically defective surface. Furthermore, the filling of the thick side ahead of the thin side creates a pressure imbalance generated by the 5 to 10 tons/sq. in. injection pressure that can cause the core to deflect toward the thin side, further aggravating the difference in wall thickness. This pressure imbalance will contribute to mold damage and make part production difficult if not impossible. We may conclude that the wall uniformity throughout the circumference must be within narrow limits, such as ± 0.002 in., whereas the thickness in general may vary from the specified value by ± 0.005 in.

Flow Patterns

Ultimately, part quality can be considered a direct outcome of a plastic melt's flow behavior in its mold cavity or cavities. Excessive restrictions and obstructions to the flow of material spell trouble in injection molding. Some examples of reduced-flow problems are illustrated in Figures 11-10 through 11-18.

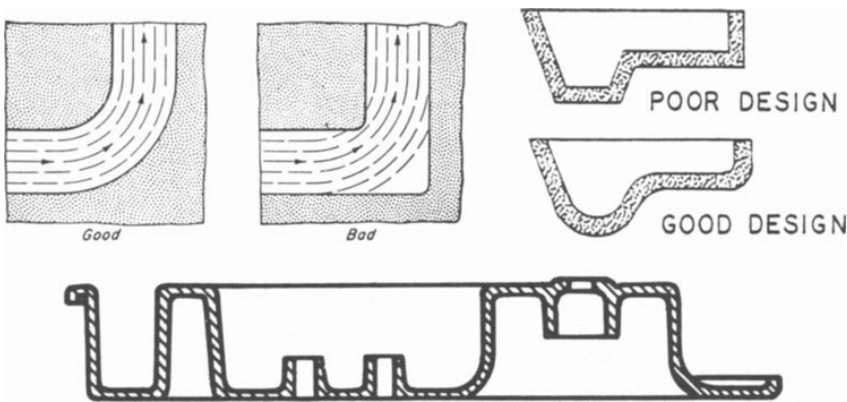


Figure 11-10. A nominal thickness maintained throughout a part can simplify its melt flow. Good design has a minimum exterior radius of $1\frac{1}{2}$ times the wall thickness and a minimum of $\frac{1}{2}$ its thickness, which maintains uniform section thickness.

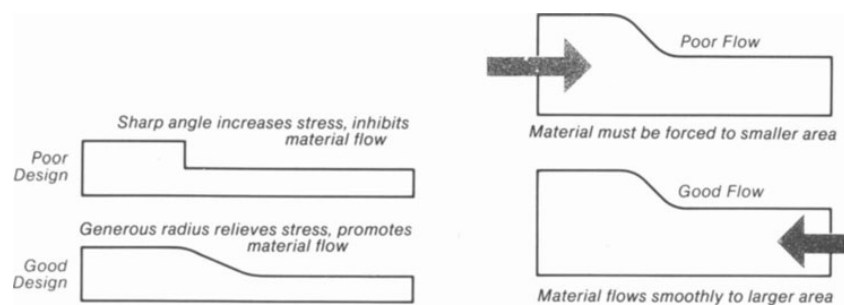


Figure 11-11. Approaches to consider when making changes in wall thicknesses.

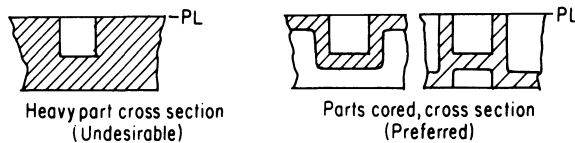


Figure 11-12. Parts having heavy cross-sections are subject to longer cycles and cures, laminations or skins, blisters, warpage, and increased fabricating costs.

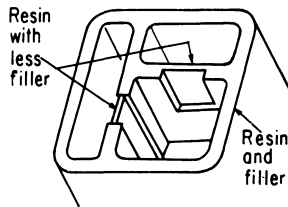


Figure 11-13. When molding an RP, thin sections sometimes lose strength, because fibers do not flow into a narrow space unless a suitable moldable material is used.

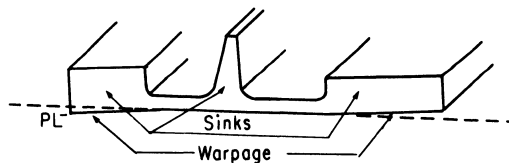


Figure 11-14. Avoid having uneven sections, which cause distortion, warpage, cracks, sinks, and strains because of differences in shrinkage from one section to another. Where this situation exists or at least usually exists the problem is normally eliminated by changing the process controls which in turn usually requires a longer cycle time.

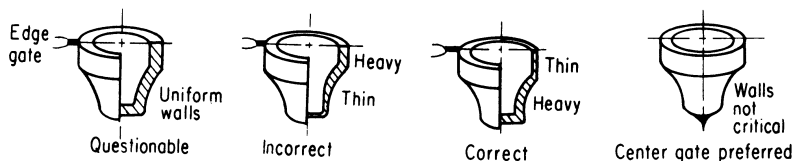


Figure 11-15. The design of wall sections contributes to flow patterns and can be controlled to obtain the best end-product results.

DESIGN FEATURES THAT INFLUENCE PERFORMANCE 805

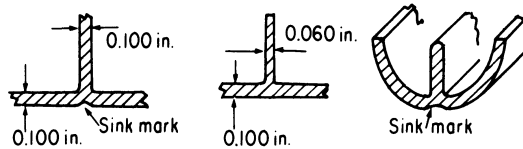


Figure 11-16. The thicknesses of adjacent walls and ribs should be about 60 percent of the thickness of the main bodies to reduce the possibility of sink marks and promote better flow.

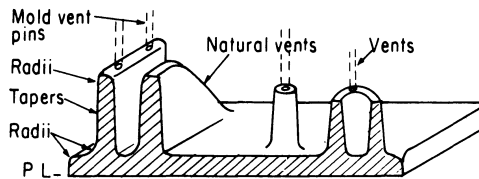


Figure 11-17. Sharp corners, straight sides, and improper venting impede flow, resulting in strains and possible cracks. Optimum flow requires using maximum radii at corners, reasonable inside and outside tapers, as well as proper vents at mold-parting lines, pockets, and blind holes.

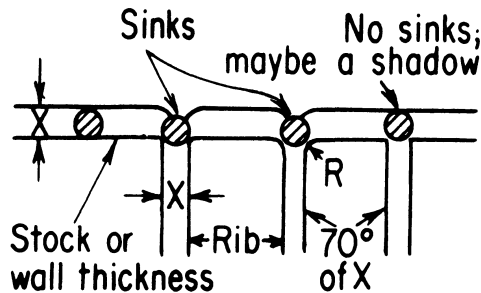


Figure 11-18. A crude but effective method for locating sink marks and designing them “out” of plastics parts is in effect to “roll a ball” down the wall’s thickness; if it permits a sink, the part will be marked.

Parting Lines

Parting lines (PLs) on the surface of a molded product, which are produced by the parting line of the mold, can often be concealed on a thin, inconspicuous edge of the part. Doing so preserves the good appearance of the molding and in most cases eliminates the need for any finishing. Figures 11-19 through 11-26 show parting-line locations on various part configurations.

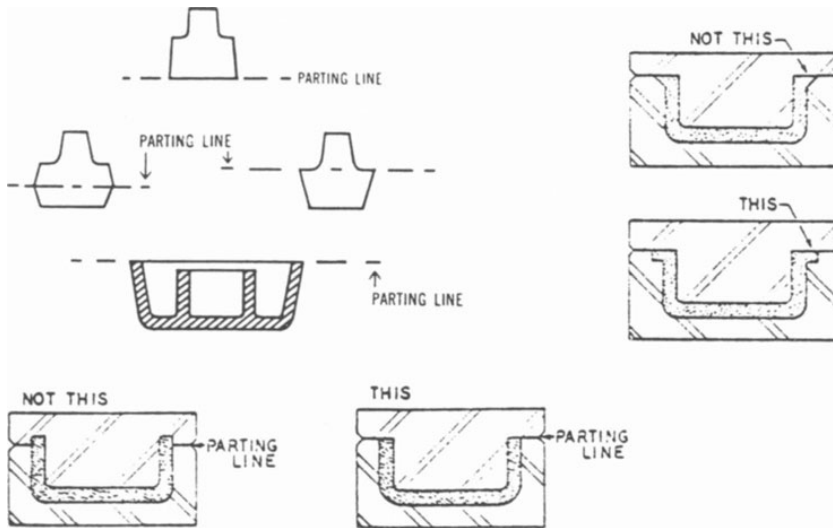


Figure 11-19. Examples of parting line locations. The extreme right diagram shows that having sharp corners could cause poor dimensional control or possibly nonflat surfaces with inadequate mold cooling.

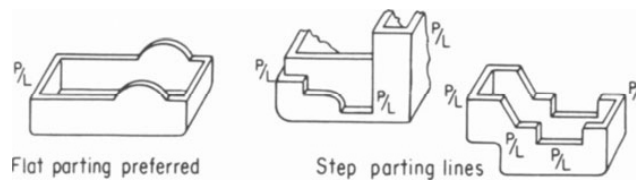


Figure 11-20. Consider the parting lines when designing parts that may require odd or different radii, contours, and stepped parting lines.

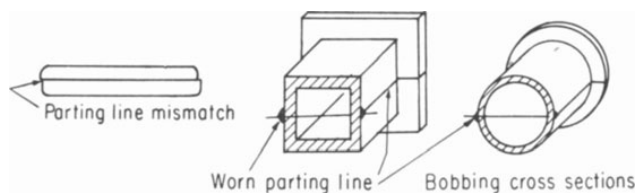


Figure 11-21. Excessive wear on mold parting lines can create a mismatch on a molded part that will appear greatly exaggerated (a 0.0003 in. mismatch can appear to be 0.020 in.) or can create burrs from 0.001 to as much as 0.010 in.

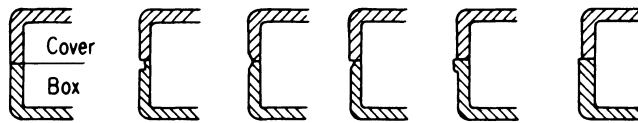


Figure 11-22. An example of a series of possibilities for designed mismatches.

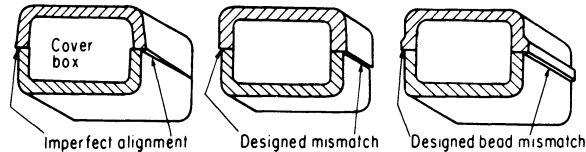


Figure 11-23. A mismatch in alignment of two molded parts (such as a box and cover) usually is traceable to part warpage or difference in shrinkage; the misalignment at the parting line appears to be improved when a bead or a designed mismatch is utilized.

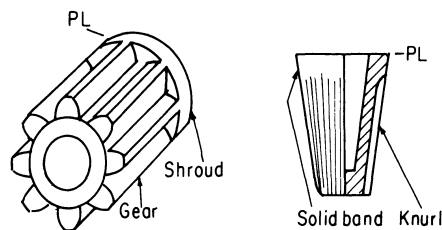


Figure 11-24. Allowing parting-line flash in gear teeth and on knurled parts requires expensive deflashing operations. To prevent flash, add a shroud to the gear or a solid band or bead to the knurl at the mold-parting line.

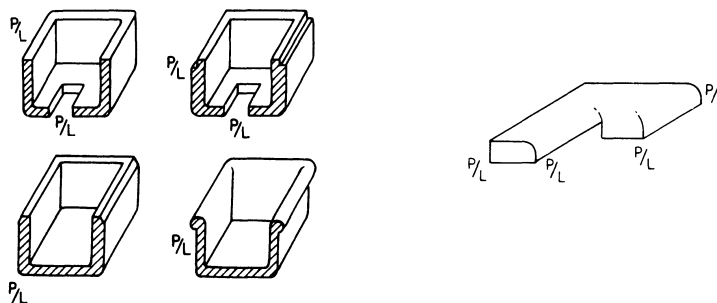


Figure 11-25. Four possibilities for locating parting lines on assembly parts, boxes, and covers while yet maintaining good aesthetics.

808 DESIGNING WITH PLASTICS AND COMPOSITES: A HANDBOOK

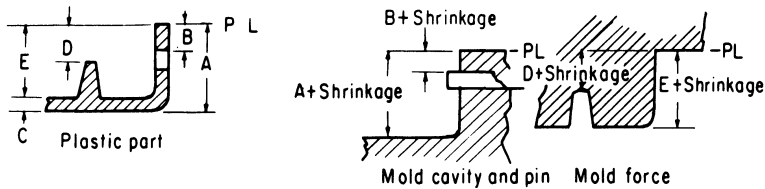


Figure 11-26. The dimensions and tolerances given for parting lines should include on the final dimensions allowances for potential flashing conditions. All molds for TPs or TSs can open and flash to some extent, depending on the mold design and construction, the melt pressure, the mold-clamping force, and the type of material. For example, if the flash is 0.003 in. at the mold-parting lines, part dimensions A, B, C, D, and E will increase 0.003 in. (*left diagram*). The drawing at the right shows how to estimate mold components.

Gate Sizes and Locations

Because of high melt pressure, the area near a gate is highly stressed, both by the frictional heat generated at the gate and the high velocities of the flowing material. Using a small gate is desirable for separating the part from the feed line, but not for a part with low stresses. Gates are usually two thirds of a part's thickness. If they are that large or larger it will reduce frictional heat, permit lower velocities, and allow the application of higher pressures for increasing the density of the material in the cavity. The product designer should caution the tool designer to keep the gate area away from load-bearing surfaces and to make the gate size such that it will improve the quality of the product. Some examples regarding the design of gates are given in Figures 11-27 through 11-32 [12].

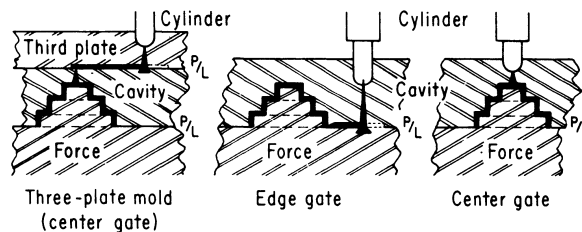


Figure 11-27. Injection molds are especially suitable for producing parts to meet different mold styles, as shown in these three examples.

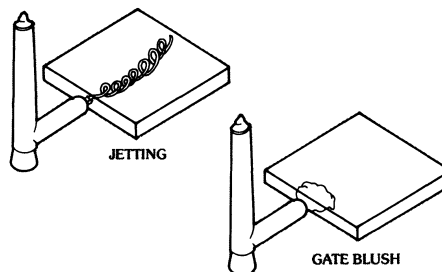


Figure 11-28. Examples of some melt flows using too small a gate. The melt should fill the cavity uniformly.

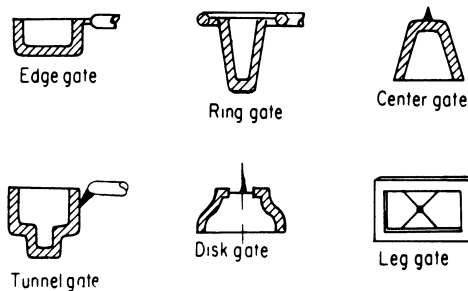


Figure 11-29. Among the various methods available for gating are edge, ring, center, tunnel, disc, and leg gates. Consider the material and design factors before selecting the type of gate.

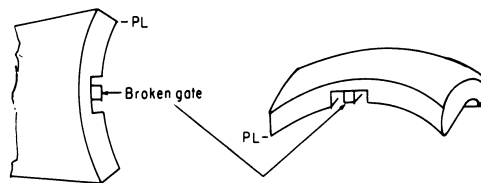


Figure 11-30. Gate breaking and clipping are low-cost removal methods when the part design permits locating a recessed gate in a hidden area, as in this handle. This type of problem is eliminated by using hot runner molds for TPs and cold runner molds for TSs.

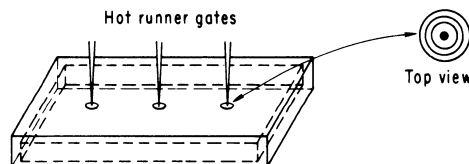


Figure 11-31. In molding a large, flat TP surface using hot or insulated runners, having one or more small gates can help reduce warpages. One way to camouflage the resulting gate scars is to use the bull's-eye design shown (with hot runners no gate problem develops).

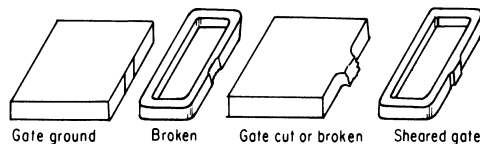


Figure 11-32. Some gates must simply be cut, sheared with fixtures, ground, or finished, but those broken off from the parts to save finishing costs could have their recesses or protrusions remain.

Tapers of Draft Angles

It is desirable for any vertical wall of a molded product to have an amount of draft that will permit its easy removal from a mold. Figures 11-33 and 11-34 show two basic conditions in which draft is a consideration. The first example is the most desirable application of the draft angle. The amount of draft may vary from $\frac{1}{8}$ degree up to several degrees, depending on what the circumstances permit. A fair average may be from $\frac{1}{2}$ degree to 1 degree. When a small angle such as $\frac{1}{8}$ degree is used, the outside surface—the mold surface producing it—will require a high directional finish, to facilitate removal from the mold.

In the other example, as shown in Figure 11-34, there is a separating inside wall that should generally be perpendicular to the base. The draft in this case should be on the low side ($\frac{1}{8}$ degree) so that additional material usage is small, the possibility of having voids close to the base is avoided, and increased cycle time in manufacturing is minimized. Here again the vertical molding surfaces will demand a much higher surface finish, with polishing lines in the direction of part withdrawal. On shallow walls the draft angle can be considerably larger, since the influence of the enumerated drawbacks will be minor. The designer should be cognizant of the need for drafts on vertical walls. If problems are encountered during the removal of parts, stresses can result, the shape of the product can be distorted and surface imperfections be introduced.

Some examples of different approaches to the design of drafts are shown in Figures

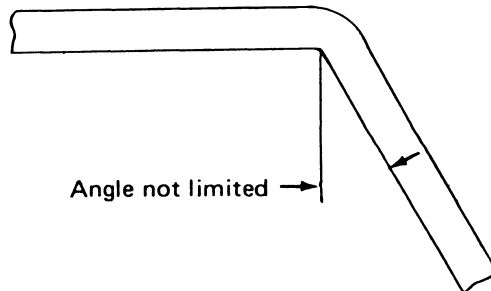


Figure 11-33. External wall taper.

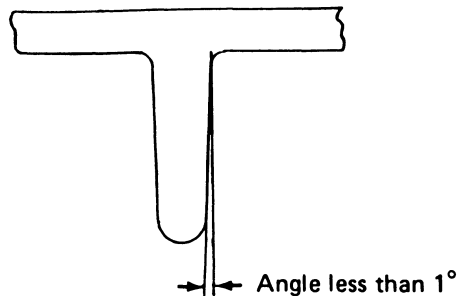


Figure 11-34. Internal wall taper.

DESIGN FEATURES THAT INFLUENCE PERFORMANCE 811

11-35 through 11-38. One of the difficulties when applying draft to a part is the creation of heavy walls. The potential problem of removal can be remedied by the using parallel drafts on walls, as shown in Figure 11-38, where the walls are kept uniform. A guide to determining the amount of dimensional change required due to the draft angle is given in Figure 11-39.

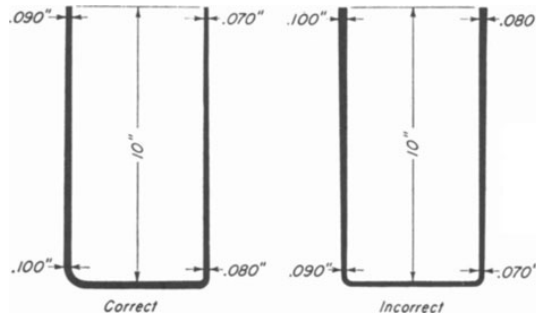


Figure 11-35. An example of side-wall taper for long-draw products.

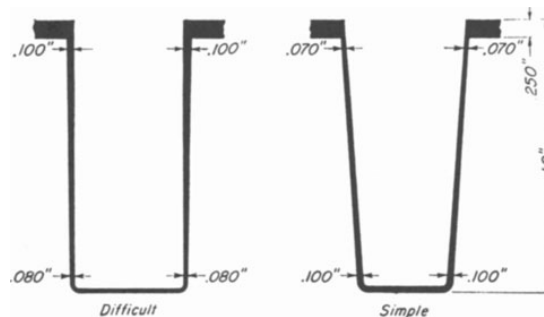


Figure 11-36. An example of designs for long-draw products. The left view has little clearance, but the right side is simplified by the clearance allowed by the walls' taper.

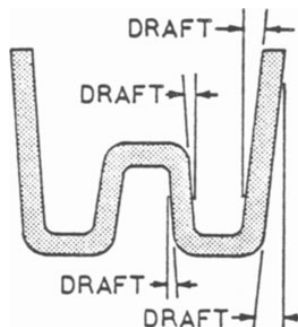


Figure 11-37. An example of using multiple drafts to permit ease of part removal.

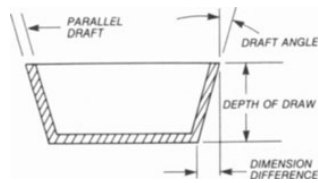


Figure 11-38. Using parallel drafts with heavy walls.

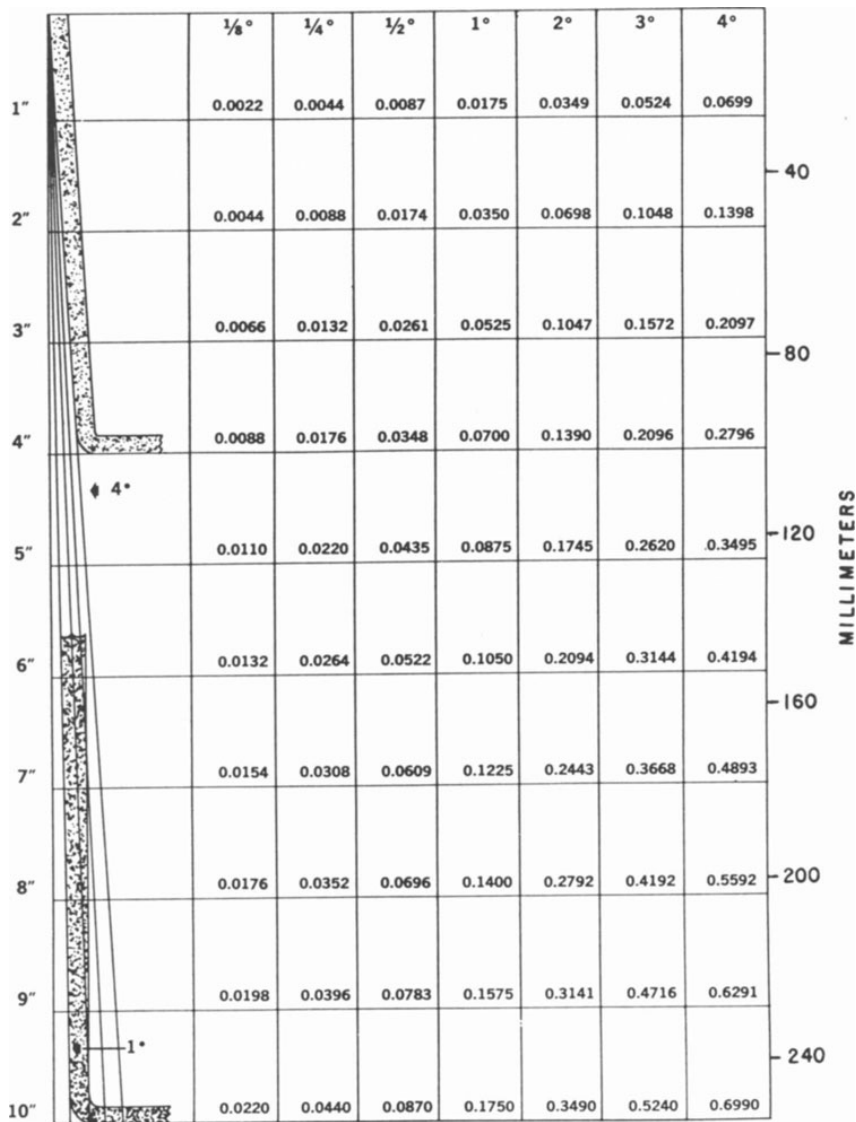


Figure 11-39. The relation of the degree of taper per side to the dimension in in./in.

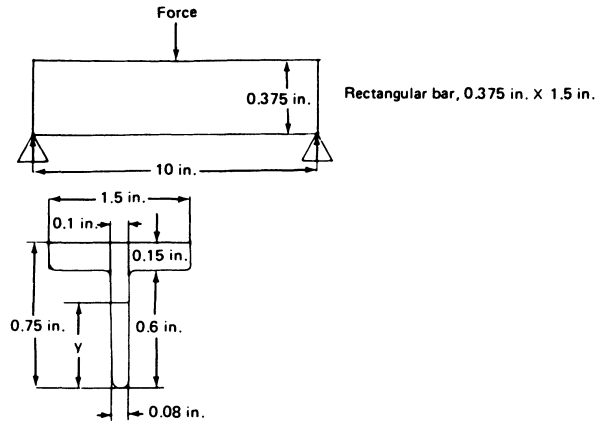


Figure 11-87. A single-rib shape with good moldability that gives a section modulus and moment of inertia equivalent to a rectangular bar.

result in high-quality products. In addition to ribs, other features protruding from a wall, such as bosses or tubular shapes, should be treated similarly as far as transition radius, taper, and minimal material usage are concerned. The same principles are involved. Identical ill effects can be expected unless the recommended practices are incorporated.

Geometric Structural Reinforcements

Besides ribs, there are other methods of improving section properties (see Chapter 5). Many of these can often be designed into functional or appearance features for the product. Basically, to increase load-carrying ability or stiffness it is necessary to increase either the properties of the plastic material or the section properties of the structure. Improving the material can be beneficial in certain cases by changing the grade or type, compounding or alloying, and incorporating fillers or fiber reinforcements (see Chapters 2–7). In regard to the structure, increasing the section properties (namely the moment of inertia and the section modulus) is usually required. As previously described, thickening wall sections will often prove a practical means of increasing section properties, but there can certainly be economic limitations in terms of material usage and molding cycles. Some typical

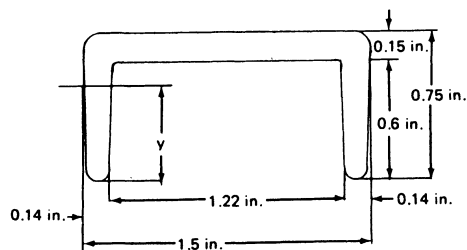


Figure 11-88. A two-rib shape with good moldability that gives a section modulus and moment of inertia equivalent to a rectangular bar.

838 DESIGNING WITH PLASTICS AND COMPOSITES: A HANDBOOK

examples of these structures and potential problems to consider are shown in Figures 11-89 through 11-91 [2].

Some geometric shapes that provide the designer with alternate methods of increasing part supports include gussets, corrugating, and doming (see Chapter 5). Gussets are supporting structures for either the edge of a part or bosses. The design guidelines for gusset thicknesses, spacing, and taper or draft are the same as for ribs. The dimensions given in Figure 11-91 for height, length, and spacing are the lowest acceptable dimensions for good gusset design.

Corrugating and doming provide the designer increased part performance without having to add ribs. Of these two methods, corrugating is the more effective. The alternative to corrugating is doming (see Fig. 11-89). When a part is domed, its wall is molded in a convex shape. In some cases this method may be preferred to corrugating for aesthetic purposes. From a structural standpoint, though, doming does not offer the reinforcement rigidity of corrugating.

Snap Joints

A snap joint is economical in two respects: it allows the structural member to be molded simultaneously with the molded part, and it allows rationalizing the assembly, compared with such other joining processes as screws. Table 11-5 provides a comparison of its advantages and disadvantages. The design guidelines that should be taken into consideration for obtaining the desired functions are described in Chapter 5 [409]. Some examples of the various types and their design considerations are shown in Figures 11-92 through 11-94.

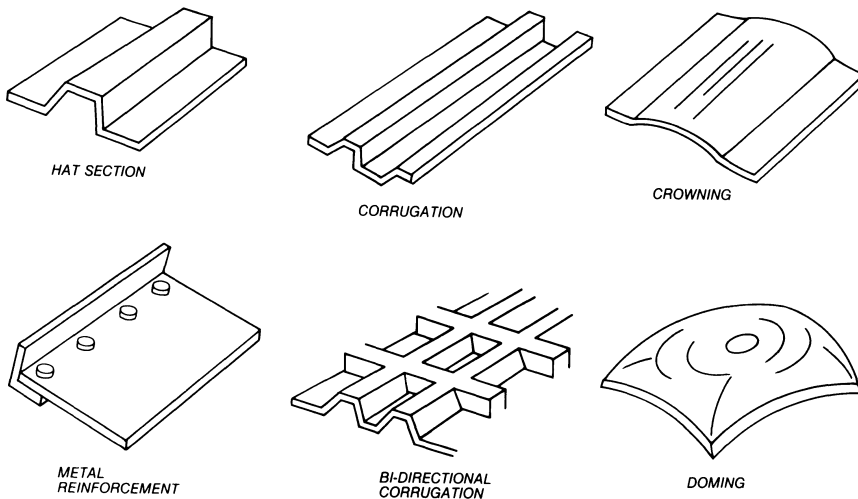
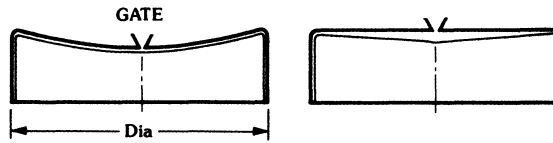
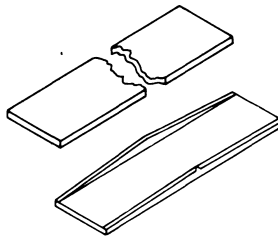


Figure 11-89. Examples of geometric structural reinforcement techniques.

Oil canning effect; left view is with even wall and other view shows redesigned double-tapered wall.



Long, flat part (top) could tend to warp; add ribs to correct problem.



Warpage allowance and direction should be shown on the design drawing so that cooling fixtures, type plastic and molding techniques may be determined to achieve optimum performance in the molded part.

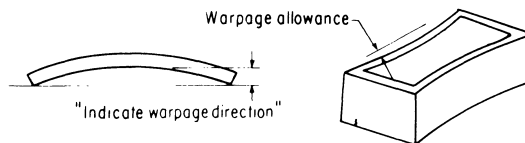


Figure 11-90. Examples of potential problems with different shapes.

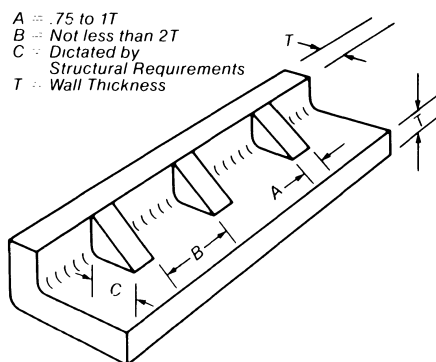


Figure 11-91. Guidelines for designing a gusset.